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GEOGRAPHICAL HANDBOOK SERIES
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PACIFIC ISLANDS

VOLUME I

GENERAL SURVEY

August 1945

NAVAL INTELLIGENCE DIVISION

This volume was produced and printed for official purposes during the war 1939/45

PREFACE

In 1915 a Geographical Section was formed in the Naval Intelligence Division of the Admiralty to write Geographical Handbooks on various parts of the world. The purpose of these handbooks was to supply, by scientific research and skilled arrangement, material for the discussion of naval, military, and political problems, as distinct from the examination of the problems themselves. Many distinguished collaborators assisted in their production, and by the end of 1918 upwards of fifty volumes had been produced in Handbook and Manual form, as well as numerous short-term geographical reports. The demand for these books increased rapidly with each new issue, and they acquired a high reputation for accuracy and impartiality. They are now to be found in Service Establishments and Embassies throughout the world, and in the early years after the last war were much used by the League of Nations.

The old Handbooks have been extensively used in the present war, and experience has disclosed both their value and their limitations. On the one hand they have proved, beyond all question, how greatly the work of the fighting services and of Government Departments is facilitated if countries of strategic or political importance are covered by handbooks which deal, in a convenient and easily digested form, with their geography, ethnology, administration, and resources. On the other hand, it has become apparent that something more is needed to meet present-day requirements. The old series does not cover many of the countries closely affected by the present war (e.g. Germany, France, Poland, Spain, Portugal, to name only a few); its books are somewhat uneven in quality, and they are inadequately equipped with maps, diagrams, and photographic illustrations.

The present series of Handbooks, while owing its inspiration largely to the former series, is in no sense an attempt to revise or re-edit that series. It is an entirely new set of books, produced in the Naval Intelligence Division by trained geographers drawn largely from the Universities, and working at sub-centres established at Oxford and Cambridge. The books follow, in general, a uniform scheme, though minor modifications will be found in particular cases; and they are illustrated by numerous maps and photographs.

The purpose of the books is primarily naval. They are designed first to provide, for the use of Commanding Officers, information in a

comprehensive and convenient form about countries which they may be called upon to visit, not only in war but in peace-time; secondly, to maintain the high standard of education in the Navy and, by supplying officers with material for lectures to naval personnel ashore and afloat, to ensure for all ranks that visits to a new country shall be both interesting and profitable.

Their contents are, however, by no means confined to matters of purely naval interest. For many purposes (e.g. history, administration, resources, communications, etc.) countries must necessarily be treated as a whole, and no attempt is made to limit their treatment exclusively to coastal zones. It is hoped therefore that the Army, the Royal Air Force, and other Government Departments (many of whom have given great assistance in the production of the series) will find these Handbooks even more valuable than their predecessors proved to be both during and after the last war.

J. H. GODFREY
Director of Naval Intelligence
1942

The foregoing preface has appeared from the beginning of this series of Geographical Handbooks. It describes so effectively their origin and purpose that I have decided to retain it in its original form.

This volume has been prepared for the Naval Intelligence Division at the Cambridge sub-centre (General Editor, Dr H. C. Darb). It has been mainly written by Dr J. W. Davidson, Dr Margaret Davies, Dr Raymond Firth, Dr L. Hawkes and Dr P. W. Richards, with contributions from Mr A. E. P. Collins, Mr Adrian Digby, Dr J. P. Harding, Professor A. A. Miller, and Dr Charles Wilcocks. The maps and diagrams have been drawn mainly by Mr A. O. Cole, Miss K. S. A. Froggatt, Miss F. Hands, Miss M. Hart, and Mrs Gwen Raverat. The volume has been edited by Dr Raymond Firth and Dr J. W. Davidson.

E. G. N. RUSHBROOKE
Director of Naval Intelligence

August 1945

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INTRODUCTION

Significance and Status of the Pacific Islands: Plan of the Handbook

SIGNIFICANCE AND STATUS OF THE PACIFIC ISLANDS

Though the Pacific ocean is so vast, the land area of the islands which it contains is relatively small. The total is about 400,000 sq. miles, and of this roughly 90% is comprised by New Guinea. The population of the islands is only about $2\frac{1}{2}$ millions. Only a few islands are known to possess resources of much importance in the world economy. In recent years, however, the importance of some islands for the development of air communications has become evident, and students of political and military matters have been made aware of the strategic significance of the region as a whole to the powerful states round the borders of the Pacific basin. This significance was forcibly driven home after the outbreak of war with Japan in 1941. The names of many Pacific islands are now generally known, and something of their importance is widely understood. The rapid changes brought about by the war, however, make more difficult the presentation of an exact picture of the geography of the region. These changes, together with the basic factors of physical, social and political diversity, make it necessary for a Handbook on the Pacific islands to follow a somewhat different treatment from that adopted in dealing with a compact geographical and political entity, such as a European country.

Conditions of life in the Pacific islands depend very largely on the oceanic environment. Some account of the Pacific ocean—its size and form, its climate, its fauna, etc.—is therefore necessary to explain the characteristics of the islands. Vegetation is largely influenced in the same ways—some plants have been spread through the agency of ocean currents; others have been introduced by human travellers; practically all the plant life of the coral islands is affected by the surrounding seas. The history of the islands, especially in its earliest phases, is largely one of sea travel—of voyages of discovery and exploration, of trade between islands and with the world beyond, of the transport of labour from one island group to another or to the neighbouring continents, of the visits of mission-

aries to isolated island communities. Economically, whaling and the search for pearls and other products of the reefs and lagoons have been important factors in the development of the islands, and fishing is still one of the main means of livelihood of a large part of the native population. Most of the towns in the islands owe their importance largely to the fact that they are also ports; and, despite recent and prospective developments in air communication, the life of most island communities will remain dependent on shipping for a long time to come.

Politically, the Pacific island territories are all in some degree dependencies of more powerful states outside the island region. These political linkages do not always follow the natural geographical groupings. Thus, United States territory is to be found (in Samoa) in the middle of a ring of British territory, or (in Guam) surrounded by islands formerly held by the Japanese under mandate from the League of Nations; the French colony of New Caledonia is adjacent to Australia, but separated by half the width of the Pacific from French possessions in the Eastern Pacific; and, again, some groups of islands are divided between separate administrations or administered jointly by two Powers as a condominium. The political status of the more important territories (as in 1939) is shown in the following Table:

Pacific Islands: Political Status †

Controlling Power	Area	Status
Britain		
(i) United Kingdom	Fiji (including dependency of Rotuma)	Colony
	Tonga	Protected State
	Solomon islands (excluding Bougainville and islands northward)	Protectorate
	Gilbert and Ellice islands, Ocean island, and some small central Pacific dependencies	Colony
	Pitcairn group	Colony
(ii) Australia	Papua	Territory
	North-east New Guinea (including northern Solomon islands	Mandated Territory
	Norfolk island	Territory
	Lord Howe island	Part of the State of New South Wales

Pacific Islands: Political Status—continued

Controlling Power	Area	Status
(iii) New Zealand	Western Samoa	Mandated Territory
	Cook islands	Territory
	Niue	Territory
	Tokelau group	Territory
	Kermadec islands	Territory
(iv) United Kingdom, Australia and New Zealand	Nauru	Mandated Territory (administered by Australia)
Britain (United Kingdom) and France	New Hebrides	Condominium
Britain (United Kingdom) and United States	Canton and Enderbury	Condominium
France	New Caledonia and Loyalty islands	Colony
	Uvea (Wallis island) and Futuna	Protectorate
	French Establishments in Oceania (Society islands, Tuamotu archipelago, Mangareva group, Austral islands and Marquesas)	Colony
United States of America	Hawaiian islands	Territory
	American Samoa	Dependency under naval jurisdiction
	Guam	Dependency under naval jurisdiction
Netherlands	Dutch New Guinea	Part of the Outer Provinces of the Netherlands East Indies
Japan	Marianas, Caroline islands, and Marshall islands	Mandated Territory
	Bonin islands	Part of the Prefecture of Tokyo

† The position regarding sovereignty in the Pacific immediately prior to the war of 1914–18 is shown in Fig. 95; administrative areas in the Eastern and Western Pacific respectively, as at the outbreak of war in 1939, are shown in vol. II, Fig. 2 and vol. III, Fig. 2.

PLAN OF THE HANDBOOK

Though the oceanic setting gives to the Pacific islands many common characteristics, physical and social, the region is so large and many of the islands are so isolated that great diversity remains. In treating the region as a unit, only very broad generalization is possible, and much that is of primary importance in particular areas has perforce to be omitted or passed over very briefly. The Handbook is therefore divided into the present introductory volume, which gives a general survey of the Pacific ocean and of the islands as a whole, and three

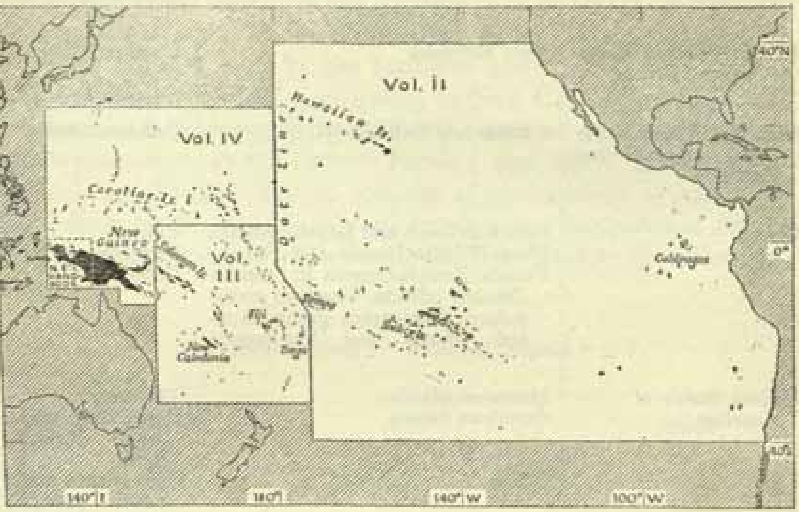

Fig. 1. Key map to the Handbook

The unshaded areas contain the islands described in volumes II, III and IV.

regional volumes, which describe the characteristics of each group or island in turn. Volume II covers the islands of the Eastern Pacific; volumes III and IV deal with those of the Western Pacific. (The area covered by each of the regional volumes is indicated in Fig. 1.) For the description of each group the same system of headings is followed as far as possible; and, for the major areas, the general review is followed by a description of the physical characteristics and social and economic conditions of each island individually. A bibliographical note is given for each group of islands.

Plate 1. The Dunantina river, New Guinea

Showing erosion forms on the southern slopes of the Bismarck range (part of the Archaean core of New Guinea). There are few high outstanding peaks owing to levelling of the core prior to uplift. Recent erosion has produced deep valleys.

Plate 2. The Watut-Tiviri watershed, New Guinea

This view in the central highlands shows recent erosion of the uplifted core. At this elevation forests are confined to valley bottoms and most of the surface is under grass.

Plate 3. The eastern barrier reef, Mangareva
A view looking north at high tide, showing the sea breaking against the steep coral beach. Two small reef islets can just be seen on the horizon.

Plate 4. Tarawa, Gilbert islands
In the foreground is Betio (Bititu) island, on which was the principal settlement before the war; the airstrip built by the Japanese can be clearly seen. The long narrow island running out of the photograph (towards the east) is Bairiki.

Chapter II

GEOLOGY AND PHYSICAL STRUCTURE

General Features : Types of Rocks : Age and Origin of the Pacific : Active and Extinct Volcanoes : Earthquakes : Coral Reefs : The Sculpturing of Volcanic Islands : Deposits on the Floor of the Pacific : Bibliographical Note

The Pacific ocean is bounded by fold mountains which show great instability, and earth movements and vulcanism are features of many of its 20,000 islands. A large number of these islands have been built up by corals, and, here again, there are frequent changes in the details of the landscape. East of 150° W depths are relatively more uniform and island groups are infrequent. The majority of the islands and the great ocean deeps lie west of this meridian. The island arcs are roughly concentric to Australia, and the inner islands share some of its continental rocks (Plates 1 – 2), but these become rarer in the more easterly arcs. Younger folded rocks are also well developed in all these arcs. Coral reefs are frequent and, as one passes towards the centre of the ocean, coral rock predominates on the surface of the islands (Plate 3). Many are wholly of coral (Fig.2). Melanesia, Micronesia and most of Polynesia are set in the west of a great ocean, the greatest unit of the hydrosphere. The majority of the Pacific islands lie in a sector of the Pacific which in area is roughly equal to the Indian ocean, and to north and east lie vast stretches of ocean, for the most part, like the North and South Atlantic, empty of island groups.

GENERAL FEATURES

The Pacific ocean has been variously defined. Two main usages of the term may be noted. It may be regarded *either* as the area bounded by the continents of North and South America, Antarctica, Australia, and Asia, and marked off from adjoining seas by Bering strait (36 miles wide) in the north and the meridians of South-east cape (Tasmania), and cape Horn in the south, *or* this area restricted by the exclusion of the bordering Bering, Okhotsk, Japan, Yellow and East China seas, and of Bass strait, and of the Californian gulf. The term 'Pacific basin' as used by geologists is a still further restricted area (p. 14).

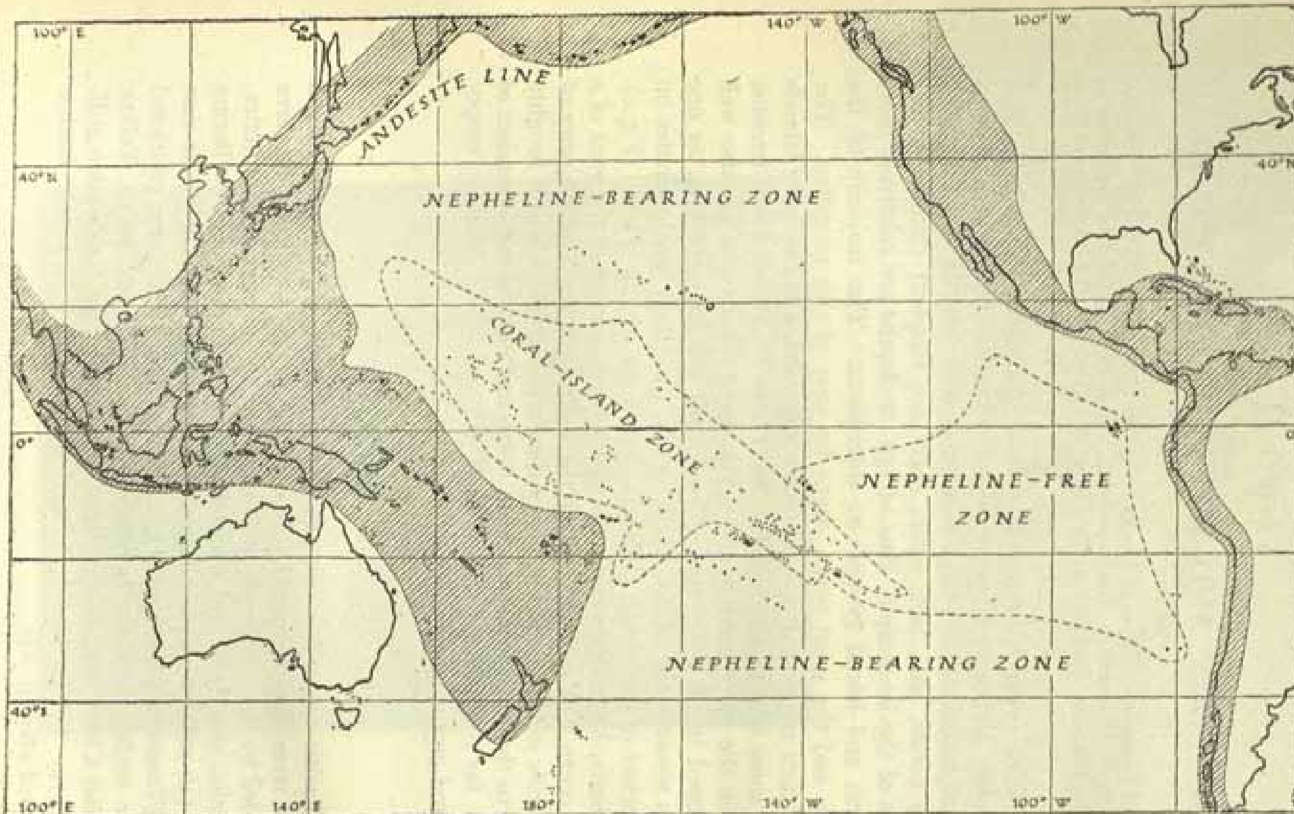

Fig. 2. Distribution of rock types in the Pacific

The Pacific basin is enclosed by the andesite line ; the andesite zone is shaded. Nepheline is a rock-forming mineral found in hexagonal crystals. The nepheline zone is a division which includes those volcanic islands in which nepheline-bearing rocks predominate or are well represented. The islands of the nepheline zone are usually in linear groupings. Based on L. J. Chubb, 'The Structure of the Pacific Basin', *Geological Magazine*, vol. LXXI, p. 290 (London, 1934).

Comparative size

The following comparative figures are of interest :

Areas (in millions of sq. miles) :	
Earth	197.0
Total lands	57.5
Total seas	139.5
Pacific (with bordering seas)	69.4
Pacific (without bordering seas	63.8
Atlantic (without bordering seas)	31.8
Average Depths (in fathoms) :	
Total seas	2,078
Pacific (with bordering seas)	2,251
Pacific (without bordering seas)	2,341
Atlantic (without bordering seas)	2,147
Volumes (in millions of cubic miles) :	
Total seas	329
Pacific (with bordering seas)	174
Pacific (without bordering seas)	170
Atlantic (without bordering seas)	78

Thus the area of the Pacific with its bordering seas is about one-third that of the earth, one-half that of the oceans, and one-fifth greater than that of the land. The Pacific ocean has a cubic content seven times as great as the bulk of all the land over sea-level. The form of the area can be realized only by examining a globe. The distance from Bering strait southwards to cape Adare, Antarctica, is approximately 9,320 miles. The point on the earth most distant from land is at 47° 30′ S, 118° 30′ W, and lies 1,560 miles from the nearest coasts of South America, Peter I island in Antarctica, and Ducie island. The distance from shore to shore across the Pacific in latitude 15° N is almost twice as great as that across the Atlantic ocean along the same parallel. While there is a relatively constricted area between the northern and southern Atlantic basins (the distance from Brazil to Liberia is roughly 1,700 miles), there is no such narrowing in the Pacific ocean. Profound differences in water circulation and in modern communications arise from this major contrast between the two oceans, and also from the fact that the Pacific, unlike the Atlantic, is shut off from the Arctic ocean.

The Ocean Floor

Despite advances in echo-sounding technique whereby depth is rapidly found by noting the time of travel of sound waves to the bottom of the sea and back, only the broad features of the form of the Pacific floor are known. The question as to whether the

floor has irregularities at all comparable with those of the land surfaces will not be resolved until sounding methods have been further developed. The most favoured opinion among geologists is that the greater part of the Pacific floor has lain below the sea for geological ages—perhaps since the time of the birth of the hydrosphere—and that therefore the varied forms of relief developed by erosion of the lands are not to be expected there. If this is so, the relief must be due either to differential movements of the sub-oceanic earth's crust or to the accumulation of materials from submarine volcanoes.

The floor is covered by an unknown thickness of soft fine-grained marine deposits (p. 52). As at present known it is generally level, with elongate gentle rises and depressions with straight-line or slightly curving trends. Many of the rises support lines of islands. In addition, there are the elongate 'great deeps', a characteristic feature of great stretches of the border of the Pacific. These deeps are commonly called 'troughs' or 'trenches'—terms which may give a false idea of depressions in which the sides do not attain slopes of more than 7° and are commonly even more gentle. It must be borne in mind that in drawing sections across ocean floors it is usual greatly to exaggerate the vertical scale, with a consequent unnatural steepening of slopes; the sections of Figs. 3–5 will illus-

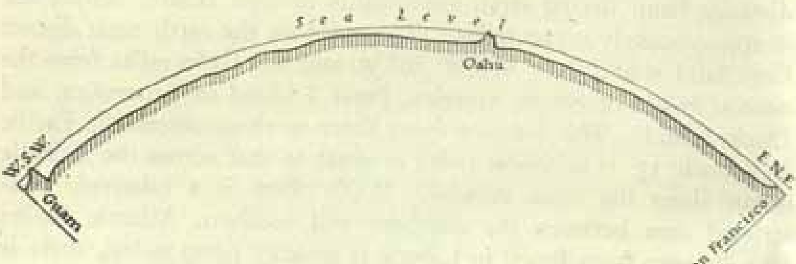

Fig. 3. Section across the Pacific basin

This section extends over a quarter of the earth's circumference. The vertical scale is exaggerated 30 times. Based on F. A. V. Meinesz, *Gravity Expeditions at Sea*, vol. II, plate 1 (Delft, 1934).

trate this point. The deeps are situated not in the middle of the ocean, but either near to and parallel with the continental borders or along lines of islands marking the borders of the geologist's 'Pacific basin' (Fig. 7). Fig. 6 shows that many of the deeps are arcuate in plan with high land on one side—usually on their concave side; they are accordingly known as 'fore-deeps," i.e., the ocean

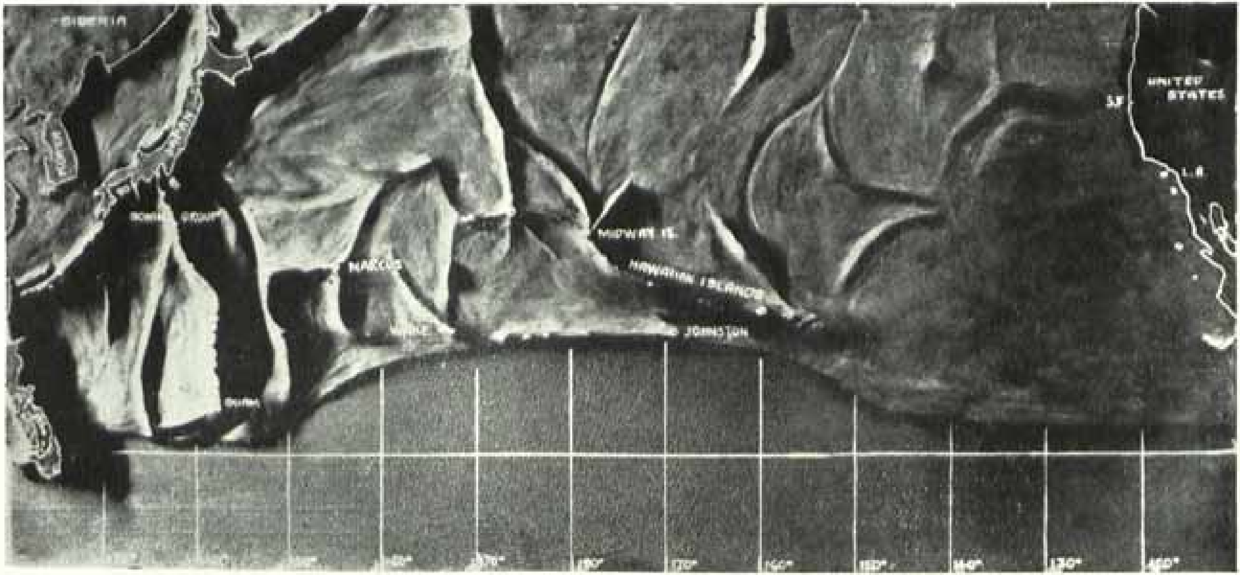

Plate 5. Model of the north Pacific floor

This model shows the submarine ridges and deeps ; the lighting is from the west side. It may usefully be compared with the folding map at the end of the volume.

Plate 6. Columnar basalt, Ponape
Basalt is well developed in the Jokaj cliff in the north-central part of Ponape.

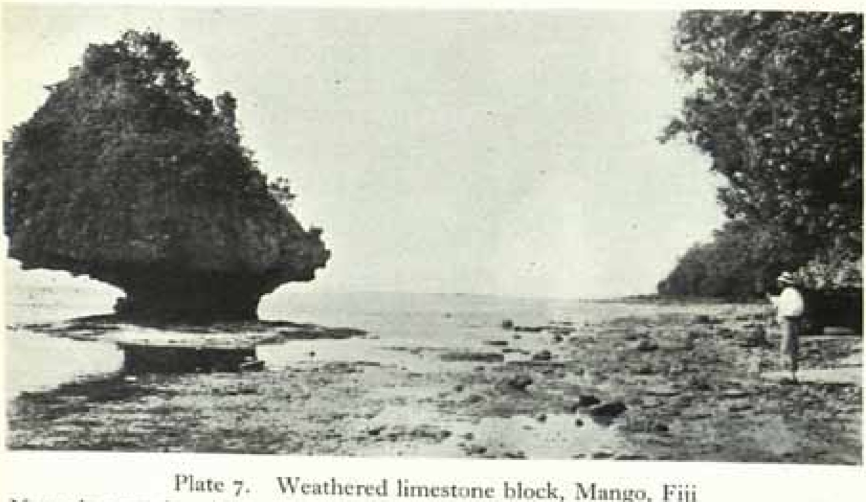

Plate 7. Weathered limestone block, Mango, Fiji
Note the way in which this limestone boulder has been undercut by the waves.

hollows in front of the land elevations. The marginal lands of the Pacific are all mountainous and the deeps commonly lie closest to the mountains where they are highest. Great earth movements have occurred in these marginal areas. The maximum ocean depth recorded, 5,902 fathoms (6·7 miles), is from the Planet deep off the Philippines; this depth is about half the amount of the earth's radial polar flattening. The south-eastern sector of the Pacific is

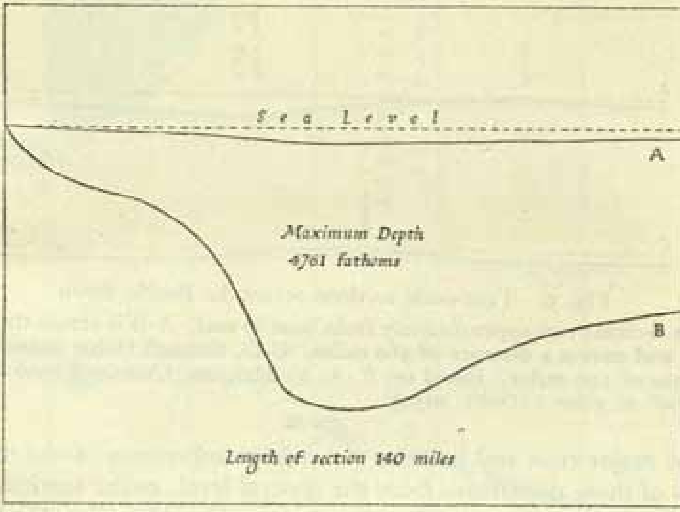

Fig. 4. Section across the Tonga deep
The true scale is shown by A. In B the vertical scale has been exaggerated 20 times. Based on various sources.

revealed on Fig. 6 as one of rather less than average depth. There are four relatively small deeps parallel to the Peruvian and Chilean coasts in this sector, viz.:—the Atacama trench, 4,175 fathoms; the deep lying off the angle of the coast where the Peruvian and Chilean coasts adjoin, 3,755 fathoms; that lying off Callao, 3,209 fathoms; and the deep which lies off Valparaiso, 3,099 fathoms. The three deepest troughs lie off coasts which slope steeply up to the high Andes. The south-eastern sector has few islands. In the Western Pacific there are many chains of islands, and off them on their eastern margins lie the fore-deeps. In addition to the great trench sounded by the *Emden* off the Philippines are deeps lying east of the Palau islands and east of Yap. The maximum sounding from the deep lying south-east of Guam and the Marianas is 5,788

fathoms. Off New Guinea and the Solomons the Bougainville trench is 5,490 fathoms deep, while the deep off New Caledonia reaches 4,139 fathoms. The long Kermadec-Tonga deep which stretches from 36° S northward to 16° S reaches 5,639 fathoms (Fig. 6).

The model (Plate 5) of part of the north Pacific floor is based on over 17,000 soundings made by the U.S.S. *Ramapo* between lat. 10° N and lat. 50° N. It gives a valuable picture of the positions and trends

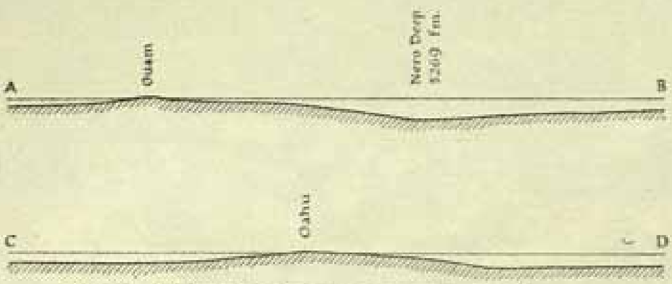

Fig. 5. True-scale sections across the Pacific ocean

These sections run approximately from west to east. A-B is across the Nero deep, and covers a distance of 360 miles. C-D, through Oahu, represents a distance of 190 miles. Based on F. A. V. Meinesz, *Gravity Expeditions at Sea*, vol. II, plate I (Delft, 1934).

of the major rises and hollows, but a false impression of the magnitudes of these departures from the general level, as the vertical scale of the model is exaggerated 50 times. The Hawaiian 'swell'—a gentle rise 600 miles wide and 1,900 miles long—trends NNW-SSE (Fig. 5, Section C-D). Shorter NE-SW rises cross its main axis and there is a suggestion that volcanic activity is more intense at the intersections. In the south Pacific is the Albatross plateau, an under-sea area of continental dimensions less than 2,500 fathoms below the surface. Its few islands do not lie along lines but are isolated volcanic piles.

The areas of the Pacific floor lying between various depths can be found from Fig. 7, which shows that, compared with the other oceans, the average depth is greater and the descent from the coasts to the general ocean floor steeper.

TYPES OF ROCKS

No samples have been obtained of the solid rocks beneath the universal cover of soft deposits (oozes, corals, etc.) on the ocean floor. Of the solid outer part of the earth 71 % is at present a 'terra incog-

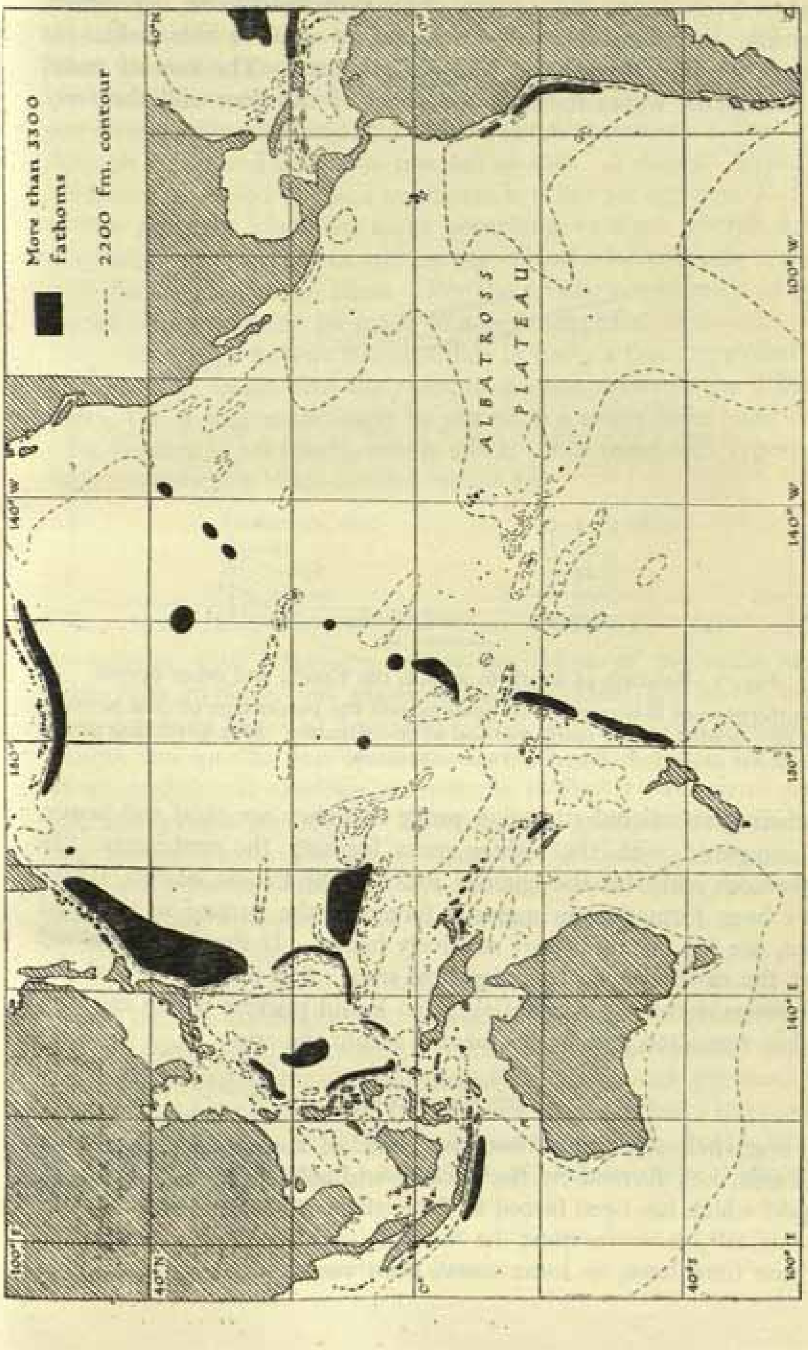

Fig. 6. Pacific ocean depths

The pecked line is the 4,000-metre contour. Areas where the depth exceeds 6,000 metres are shown in black. Based on L. J. Chubb, 'The Structure of the Pacific Basin', *Geological Magazine*, vol. LXXI, p. 291 (London, 1934).

nita' to the geologist and it is one of his dreams that one day means, scientific and financial, will be found to explore this field. At present we have to rely on indirect evidence. The rate of travel of earthquake waves through the rocks of the floor and the force

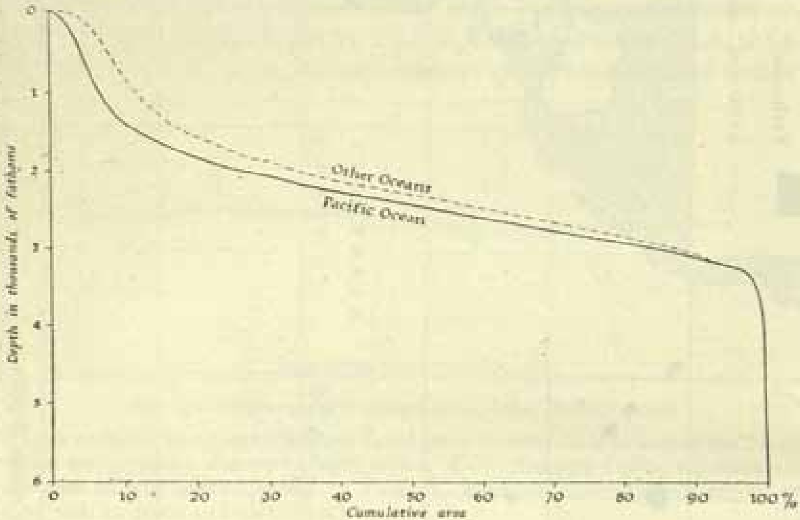

Fig. 7. Relation of depth to area in the Pacific and other oceans

The purpose of this curve is to demonstrate the percentage of area between any two depths by the usual method of co-ordinates. Seas bordering on the Pacific are excluded. Based on various sources.

of their gravitational attraction prove that they are rigid and heavy, as compared with the lighter rocks forming the continents. In agreement with this the igneous rocks of the Pacific islands, which have been formed from material forced to the surface in the fluid state, are for the most part relatively heavy. It should be realised that the earth is solid to a depth of over 1,800 miles, and that the volcanoes derive their materials from liquid pockets which at times and in restricted regions are formed within the crust.

Igneous Rocks

In overwhelming proportion, the rocks of the Pacific islands are volcanic, i.e., formed by the cooling and solidification of hot rock liquid which has been forced to the surface. (The student of Pacific geological literature must be warned that observations reported at one time have, in some cases, been contradicted later.) Large

continuous masses are known as lavas. Very commonly there is explosive activity due to the expansion of dissolved gases which takes place when the pressure on the liquid is reduced by its rise to the surface. This results in the dispersal of fragments which vary in size from bombs (volcanic rock masses one foot or more in diameter) through lapilli and scoriae to fine ash or tuff. A deposit formed of a mixture of variously-sized fragments is called an agglomerate.

The geologist classifies rocks according to their chemical and mineralogical composition and he has coined a bewildering number of forbidding names for them. For the precise connotation of these names reference must be made to a petrographical dictionary. To understand what follows it will suffice to know a few comprehensive terms and to realize that the amount of silica varies in the different rocks, which may accordingly be placed in a series from basic rocks poor in silica to acid rocks rich in silica. The main rock types with their approximate silica-content ranges are:

Oceanites, etc.	37–45% silica
Basalts	43–50% ,,
Andesites	47–58% ,,
Trachytes	56–66% ,,
Rhyolites and obsidians	68–72% ,,

In general, with increasing acidity the colour of the rocks passes from dark to light, but glassy rocks (obsidians) are black, unless they are very vesicular (pumice). Also, in general, with increasing acidity the specific gravity decreases from about 3·2 to about 2·4. If the rock liquid solidifies beneath the surface it cools more slowly and the crystals are larger. These coarser-grained 'plutonic' rocks are named picrite (which is oceanitic in composition), gabbro (basaltic), diorite (andesitic), syenite (trachytic), and granite (rhyolitic). Plate 6 shows a mass of columnar basalt.

Other Rocks

These include sandstones, mudstones, and limestones (Plate 7 shows a shore formation), many with a certain mixture of volcanic material and many changed (metamorphosed) by heat and pressure into quartzites, slates and marbles. Extreme metamorphism has resulted in the production of schists and gneisses—hard, finely banded rocks. The economically important phosphate rock is described in a separate section.

It may be pointed out here that continents have a base of light, coarse-grained rocks such as granite and gneiss, together with

sedimentary rocks, the older series of which are commonly highly disturbed, folded and metamorphosed.

The Inner Basin and its Islands

On a basis of rock composition the geologist separates an inner Pacific—the Pacific basin proper—from an outer one. The line of demarcation is known as the andesite line (Fig. 2) because, while basalts predominate within it, andesites are common in the islands and continental borders between it and the bounding land masses. The andesite zone lies, then, on the landward side of the Pacific basin of the geologist, and includes not only the relatively recently folded mountains of the continental borders—e.g., of the Rocky Mountain complex—but also, around the northern and western margins, many large and smaller island groups. The Philippines, Japan, and most of New Zealand lie within the andesite zone, and so do the island groups included in Melanesia, and the Carolines and Fiji. Within the Pacific basin proper the rocks of the islands are overwhelmingly basic—oceanites and basalts with very subordinate amounts of trachyte and more acid rocks. Rhyolite and obsidian are found only in Easter island and Tutuila. Erosion of extinct volcanic cones has exposed small bodies of gabbro and syenite, but no granite has been found. The islands of the coral zone (Fig. 2) are partly or wholly composed of coralline and other limestones which, however, are but cappings laid down on the tops of volcanoes.

Islands Outside the Basin

The rocks of most of the islands outside the inner basin are volcanic; but 'continental' rocks—i.e., granites and gneiss and other highly metamorphosed rocks—are found in the following island arcs: the Aleutian, Japanese, Ryukyu, Philippines, New Guinea-New Caledonia; also in Yap (Carolines), Vela (Truk), New Ireland, the Solomon islands, the Fiji-Tonga group, New Zealand, and the Kermadecs (Fig. 2). In addition, the widespread occurrence of andesites—rocks which are common in the borders of the Americas—is taken to be a sign of the presence of 'continental' rocks.

As an example of the kind of evidence which such 'continental' islands afford, Viti Levu (Fiji) may be cited. The oldest rocks are a series of volcanics with some quartzose sediments folded and metamorphosed and (apparently) intruded by granite, diorite, and gabbro. The precise age of these rocks is unknown but they are pre-Tertiary. (The following general Table is given for reference.)

Table of the Main Geological Periods

Era	*Period*
Quaternary	Recent Pleistocene
Kainozoic (*Tertiary*)	Pliocene Miocene Oligocene Eocene
Mesozoic (*Secondary*)	Cretaceous Jurassic Triassic
Palaeozoic (*Primary*)	Permian Carboniferous Devonian Silurian Ordovician Cambrian
	Pre-Cambrian or Archaean

These rocks are exposed in widely scattered regions in Viti Levu and they presumably form the base of the whole of it. They indicate an early period of mountain building followed by prolonged erosion which removed vast thicknesses of rock. Afterwards, in Tertiary times the younger rocks were laid down. These latter consist of about 4,000 ft. of volcanic rocks together with marine limestones.

It is clear that prior to the Tertiary period Viti Levu was a larger land area and the same conclusion applies for the other 'continental' islands. Some geologists advocate the former existence in the south-west Pacific of a large Melanesian continent extending east and south from Australia. This area is now largely deep sea and Fig. 6 demonstrates the scantiness of available evidence. The 'continental' islands were certainly larger in some part of pre-Tertiary times, but the extent of the former land area remains highly problematical. This matter is further discussed in a following section.

Rocks and Ores of Economic Value

As a whole, the Pacific islands are not rich in minerals of com mercial importance, though there are some important sources in

the Western Pacific, and phosphate occurs in a number of islands in both the Western and Eastern Pacific.

Phosphate

Phosphate is the only rock of economic importance in the limestone islands. It is derived from guano, the droppings of birds (though according to one theory some of the deposits may have been derived from marine sources). The chief sea-fowl forming rookeries are the sooty tern, the man-of-war hawk or frigate bird, the mutton bird (a petrel), the pelican, the bosun bird, and the gannet. These birds in the Pacific generally occupy low islands, some not more than 10 ft. high, and long before the land comes within the range of vision its position can be determined by the clouds of birds seen hovering over it. (Many of the islands on which phosphate occurs, however, have now long ceased to be bird rookeries.)

The guano is rich in soluble di-basic phosphate which is leached out by rain and spray, and the solutions act upon the limestone rock beneath, forming the less soluble tri-basic phosphate. There are intermediate stages between guano and phosphate rock, and some deposits are called guano-phosphate. Guano has been worked on islands such as Clipperton, Malden, Howland, Baker and Starbuck. Guano-phosphate is worked on islands such as Surprise, Fabre and Le Leizour of the Huon group north of New Caledonia, the Chesterfield group west of New Caledonia, and Walpole, south-east of New Caledonia. Rock phosphate is mined in Saipan and Rota (Marianas), in Peleliu, Tobi, Sonsorol and Angaur (Palau), in Ebon (Marshall islands), and in Makatea, Ocean island and Nauru. (For estimated reserves of the last three islands see vol. II, p. 208.) There are a few other minor sources also, but all likely islands in the Pacific have been examined (often two or three times by different parties searching for phosphate), but without success. Apparently the only undiscovered phosphate to be hoped for is a little recent guano deposited on islands unfrequented by man.

The discovery of phosphate on Nauru was unexpected. In 1897 an unusual-looking piece of rock was brought from Nauru to Sydney, where for three years it was used at company offices to keep a door open. It was eventually tested and found to be rock phosphate. Nauru and the neighbouring Ocean island contain the richest deposits of rock phosphate now known in the world; in the years immediately before the war they yielded about a million tons of phosphate per annum. (For further details of exports see vol. III,

pp. 351–4.) The rock occurs in the two islands at the surface under a veneer of guano-phosphate, and occupies the space between innumerable pinnacles of limestone which, after the phosphate has been dug, present a fantastically irregular landscape (vol. III, Plate 49). Phosphate is worked from between the pinnacles to a depth of 30 ft. or so at Nauru, and to as much as 65 ft. on Ocean island. There is still phosphate underfoot, but it does not pay to dig when the space between the broadening pinnacles becomes very narrow. The percentage of tri-basic phosphate is not only high, but fairly uniform; shipments average 85 and 88% of tri-basic phosphate of lime.

Nickel and Chrome

The most important sources of nickel and chrome are in New Caledonia, which, though its contribution to world production is not large, occupied before the war second place among nickel producers and about seventh place among producers of chrome. Both the nickel and the chrome in New Caledonia occur in the serpentine rocks. The nickel is in the form of garnierite, a compound of nickel and magnesium silicate, which occurs very sporadically in small discontinuous veins and pockets. The chrome occurs in the form of chromite, which is an iron chromium oxide, with certain impurities also present; it varies in colour from dark brown to black and is widely distributed, often concentrated in deposits near the surface left after the surrounding rock has been eroded away.

Gold and Other Minerals

Gold is obtained from New Guinea and Fiji, and has also been discovered in Guadalcanal in the Solomon islands, though production was interrupted by the outbreak of war. The metal also occurs in New Caledonia, in the alluvial deposits of the Diahot valley and in quartz veins in the old metamorphic rocks in the mountains around; only one mine has been seriously exploited, between 1870 and 1882.

Osmiridium has been obtained in association with gold in New Guinea, and has been exported in small quantities, and a certain amount of silver exists in New Guinea and New Caledonia. Manganese occurs in New Caledonia in the schists of the west coast, and was for a time an important export; deposits also occur in Rurutu (Austral islands), though they have not been worked, and on Babelthuap and Saipan, as well as in the Port Moresby area of Papua and

in New Britain. Copper, zinc, galena (silver-bearing lead sulphide), and cobalt have been obtained in New Caledonia and New Guinea, and small deposits of antimony have been worked on the east coast of New Caledonia. Iron occurs in small quantities in Yap and Ponape (Carolines), and in larger amount in New Caledonia. Though in the last-named island it is of low grade, it was extracted by Japanese interests immediately before the war. Surface iron ores which contain copper occur in New Guinea, and were worked before the war; the material was exported for pigment. Bauxite is found in Palau, Yap and Ponape (Carolines), and is reported to be in such quantity that it would suffice Japanese industry for twenty years; the estimated production in 1939 was about 100,000 tons of ore, yielding about 25,000 tons of aluminium. Sulphur deposits are common in the active volcanic areas, but in view of the low market prices for sulphur, are not worked to any great extent.

In addition to the sources mentioned above, prospecting in some island groups of the Western Pacific, such as the New Hebrides, the Solomons and New Guinea, indicates that there may yet be deposits of these and other minerals which will repay commercial exploitation.

Coal and Oil

All forms of coal are rather rare in the Pacific islands since the rocks are mainly recent. But coal of somewhat low quality has been worked on the west coast of New Caledonia (vol. III, p. 465), bituminous coal and lignite are found in Palau, and there are considerable deposits of anthracite coal (which, however, contains a high proportion of ash) in New Guinea. Lignite deposits, as yet not properly surveyed, occur in Rapa (vol. II, p. 253) and in Papua. Traces of petroleum have been found in New Caledonia (at Koumac), and there appear to be considerable petroleum reserves in New Guinea, where much prospecting has been done; there has already been some production of oil from Dutch New Guinea.

AGE AND ORIGIN OF THE PACIFIC

How long has the Pacific area been sea and how was the great depression formed? These are questions which it is impossible to answer with certainty and in consequence speculation has ranged over a host of possibilities. It has even been suggested that a continent has disappeared in the Pacific since the dawn of the human period and that the island populations are the remnants of continental

peoples who retreated to the tops of the mountains when the great submergence took place. In this connection it is pointed out that were Africa to subside by 15,000 feet its site would be deep ocean with (except for Ruwenzori) volcanic islands comparable with those of the Pacific. But the idea of a Pacific continent in human times is a fantasy—the Polynesian is a canoe man, not a pedestrian. Some geologists have postulated large tracts of land across the Pacific at various geological periods in order to account for the distributions of fossil animals. But there is no general agreement about this, and some think that the evidence is best explained on the basis of a permanent ocean.

The rocks above sea-level of the islands of the Pacific basin (in the geologist's terminology) are all of late geological age (Tertiary and later); the age of the rocks below them in the 'rises' is unknown. All the evidence indicates that the 'rises' are accumulations of volcanic material and that they are not upfolds of the sea floor similar to the fold ranges of the continents. Seismic evidence shows that at the boundary of the Pacific the difference in physical properties between the more rigid oceanic crust and the continental crust is traceable to a depth of about 30 miles, below which it disappears. The material near the surface of the Pacific floor does not differ significantly in physical properties from that for several hundred miles below it—a condition different from that in the continental areas. In qualification of this statement it should be noted that the smaller depth of the Albatross plateau and the extension of the seismic belt over it indicate the presence of a thin layer of lighter continental rock. The Pacific earth crust appears to be of remarkable strength compared with that of the continental crust. Loads of ice a few thousands of feet thick have pressed down the continental crust hundreds of feet, but big loads of volcanic rock in the Pacific islands have not had this effect. The shores of the islands have not been moved vertically by as much as a thousand feet during the last 60 million years, proving great stability of the ocean floor on which the islands rest. This is all the more significant as during this period there were great crumplings and uplifts of the continents which formed the Alps, Himalayas, Rockies, Andes, etc. The strongest reason for regarding the Pacific depression as a permanent one is the fact that the continents stand high and the ocean floors low because they are light and heavy masses respectively—the continents are floating rafts—and the geologist knows of no likely means by which this fundamental density difference could be reversed. In support

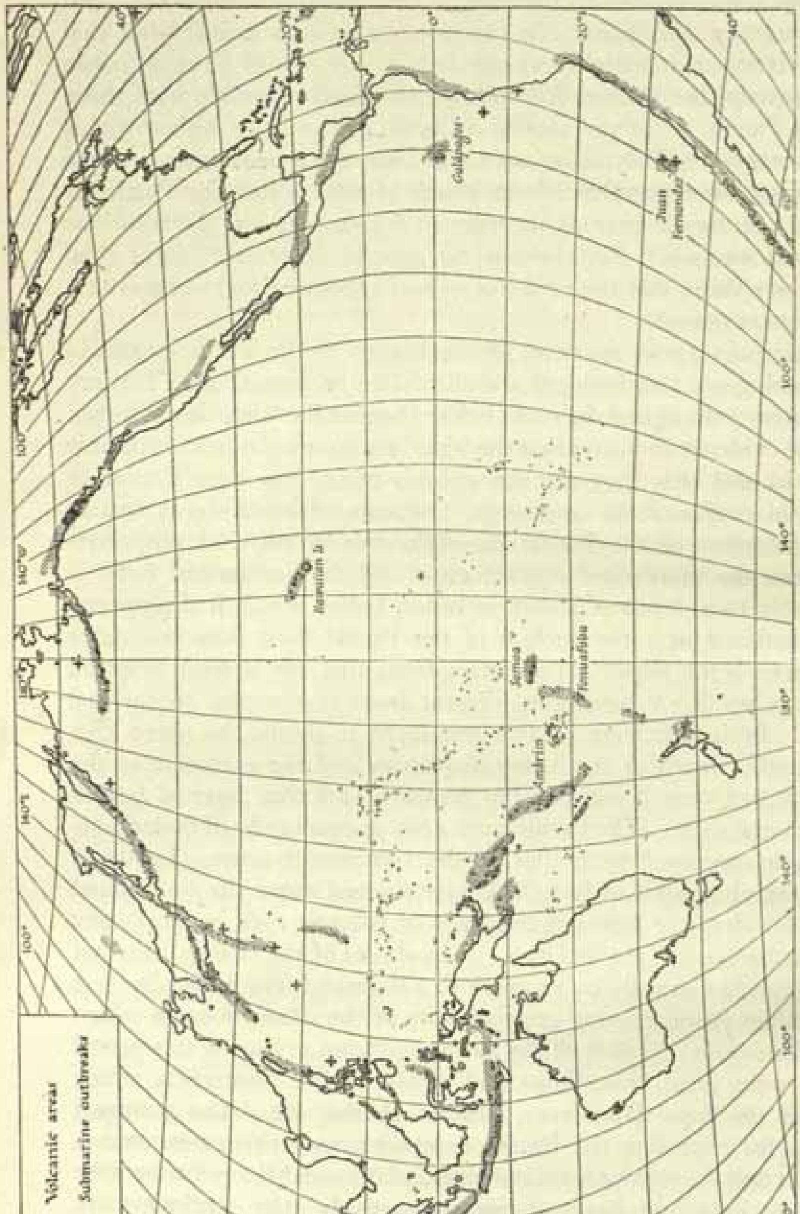

Fig. 8. Volcanic areas of the Pacific

The shaded areas are regions of active vulcanism. The crosses mark isolated outbreaks. Based on K. Sapper, *Vulkankunde*, plate 34 (Stuttgart, 1927).

of this conclusion there is no evidence that the continents have ever been covered by deep sea.

The problem of the origin of the Pacific hollow is bound up with the larger problem of the restriction of the lightest rocks of the earth to the continental sectors. The earth is built up of a series of concentric shells decreasing in density towards the surface. The shells are continuous with the exception of the outermost and lightest one, the continental crust, and why this is discontinuous and absent from the deep oceans is one of the great unsolved problems of geology. One line of thought relates the matter to the theory that the moon was once part of the earth, and it has been suggested that the Pacific depression is the scar marking the place where the moon material came off. That this is no simple conception will be realized when it is remembered that the volume of the moon is thirty times that of the Pacific. The idea may be entertained in the following form. We may imagine the earth after birth from the sun to have developed a continuous outer shell of light rock. Then as a result of tidal action the moon mass was torn from the outer and less dense shells of the earth, taking the greater part of the lightest shell with it. The specific gravity of the moon is 3·34, that of the earth 5·52. If any such event ever took place it was at the beginning of geological time. With this cataclysm one may imagine that the continental slab left behind broke up into its present fragments, which drifted towards the main Pacific 'scar' to their present positions. According to another theory this fragmentation and separation by drift has been going on through geological times and is perhaps still in progress. But all this is speculation.

The Borders of the Basin

At the borders of the Pacific basin conditions are different and exceedingly complex. Here in the north and west are the arcuate lines of islands and fore-deeps, the zone of great volcanic and earthquake activity and of uplift—the circum-Pacific belt where the earth's crust is alive. The curved lines of islands, deeps, and volcanoes appear to mark the outcrop on the world sphere of several planes which dip away from the ocean and along which differential movement is going on. Fig. 12 illustrates this conception. Determinations of the force of gravity indicate that at the deeps the earth's crust is being dragged or pushed down. The belt is one in which tangential compressive forces are in operation. One explanation

is based on the hypothesis of a cooling and contracting inner earth with the consequent growth of crustal compressive stresses in the outer layer, which find relief where the Pacific floor abuts against the weaker continental crust. The situation in the Pacific ocean regions outside the basin in past geological times is obscure. The extra-basin lines of islands contain continental rocks and appear to be the remnants of old mountain chains. The islands were larger in the past and were probably joined as long tracts of land but for the reasons given above the conception of continuous land between the islands and the continents where now are wide stretches of deep sea must be regarded with reserve.

All along the margins of New Guinea there is evidence of great earth movements, which were probably initiated in late Miocene time after the foundering of the land in the early Tertiary and reached their maximum in the Pliocene or early Pleistocene. These movements were probably responsible for the appearance of New Britain as a distinct island, and possibly for the formation of Murua (Woodlark) which has raised coral limestone platforms 200 ft. high along its north coast. In the New Guinea area and among the island arcs which curve south-eastwards from it, earth movements continued throughout the Pleistocene and into the 'recent' period of geological time; active sinking still continues along the south coast of New Guinea. As evidence of an uplift of land several platforms of coral limestone, which reach a maximum height of 1,500 ft., are found along the south-east coast of New Britain. Misima island has been affected by five distinct elevations within the Pleistocene and recent periods. Here five coral limestone terraces can be traced in an ascending series at intervals of roughly 200 ft. The flat portions of the terraces carry thin layers of sand with the remains of a recent marine fauna. Choiseul in the Solomons has limestone terraces at heights of 400, 800, and 1,200 ft. Smaller islands in this region, such as the Trobriand, Laughlan and Conflict islands have volcanic rocks or sediments of the Tertiary period which have been eroded and are capped by raised coral limestone reefs which were formed in Pleistocene times. As in other parts of the Pacific, these raised coral limestones are of fundamental importance in providing good soil for native agriculture. If the raised coral is interbedded with volcanic material (or has a thin veneer of volcanic formations as in the Duke of York islands, where the two formations form a terrace varying in height from 50 to 60 ft.), it provides a very fertile soil. This is also true of the soil weathered from low shore terraces

resulting from changes in sea level. That elevation of parts of the islands still continues is shown by a datum mark on Treasury (Solomon islands), which reveals a rise of a foot in the period 1882–1932.

Changes in Sea-Level

After a fall of sea-level, raised shores remain to mark its former position, which can be determined from them with considerable precision. With a rise of sea-level estimates of the former position can be made (albeit with less precision) from the depths of submerged shore platforms and drowned river valleys. In interpreting such evidence, there is, however, the complication that similar results are produced by vertical displacement of the earth's crust, with no change in sea-level. As the oceans are inter-communicating the effects of sea-level changes are world-wide, whereas movements of the crust are local—upwards in one region, downwards in another. The crust has been continuously undergoing differential displacement through geological time—at certain periods relatively rapidly—and it is quite impossible to discover what changes of sea-level have occurred in past geological ages. This especially applies to the Pacific region, in which earth movement has been particularly active in Tertiary times. It is only for the geologically most recent period, from the beginning of the Ice Age to the present day, that unambiguous evidence can be obtained of changes in sea-level. These changes have left their mark over all the earth, as in most areas they have been more rapid than the slow crustal movements.

Old shore levels are found at from 50 to 100 ft., while a former shore now at 15 to 20 ft. can be recognized on many coasts the world over—it is, for example, well marked in Samoa, where it is seen as a flat belt of coral debris partly covered by lava flows, and in Norfolk island. This lower raised shore is the best preserved and last to be found of the shore levels indicating a fall of sea-level. Terraces are found at lower levels than 15 ft., and indicate halts in the gradual fall of the sea to its present level.

In Rurutu in the Austral islands, deposits of coral debris and sand lie from 6 to 8 ft. and limestone shelves from 1 to 2 ft. above high water mark. In Rapa, in the same region, the limestone shelf along the shore lies at a height of 3 ft. above sea-level. There are similar shelves of coral limestone at heights of 2 ft. in Napuka (Tuamotu archipelago) and Tapuaemanu (Society islands); and at

5–6 ft. above high water in Viti Levu (Fiji), 'Eua (Tonga—Fig. 15), Moorea and Borabora (Society islands). On Tahiti these shelves take the form of low detritus-covered flats, formerly coral reefs, which lie a few feet above high water mark, and may be from 1 to 1,000 yd. wide. The emerged shore flats of Borabora are similar and vary in width from a few feet to more than 200 yd. Here, as elsewhere, the spreads of coral debris fragments and disintegrated volcanic material provide a rich loamy soil. In Yap the benches with their cover of marine sand are from 3 to 6 ft. high. Plate 8 shows five levels of erosion in Vatu Lele, Fiji.

Uplifts of the land, as distinct from changes in sea-level, produce high terraces of emerged littoral sediments around the coasts. This has been noticed in Oahu (p. 50). and is a feature of other Hawaiian islands. Elevated wave-cut platforms covered with volcanic and coral limestone boulders occur at 15 ft. in Kauai (Plate 9), and at 100 ft. in Niihau, where the platform continues inland to the base of the denuded volcanic dome at the centre of the island, and forms a flat plain broken by volcanic or sedimentary knolls which were previously islands. As an example of a fall in sea-level there is an additional series of low benches along the shore of Niihau.

The world-wide existence of submerged banks which clearly represent one-time land surfaces demonstrates a former sea-level about 300 ft. below the present one.

It is not imagined that these changes in sea-level have been due, to any appreciable extent, to changes in the capacities of the ocean basins or to losses and gains in the amount of world surface water. They can reasonably be ascribed to abstraction and addition of ocean water by transference to and from the land areas, with formation and melting of glaciers during the cold glacial and warm inter-glacial epochs respectively. It is estimated that melting away of the present glaciers of the world would result in a rise of sea-level of 150 ft., whilst at the time of maximum glaciation the sea-level was 300 ft. lower than at present. This latter estimate tallies with the position of sea-level deduced from the drowned shores. The old shore-level of 50 to 100 ft. may be ascribed to some inter-glacial period when there was less ice on the lands and more water in the sea than at present. The most recent change of level, a fall of 15 to 20 ft., may perhaps be due to the refrigeration of the climate and growth of glaciers which set in after the 'post-glacial optimum' about 4,000 years ago.

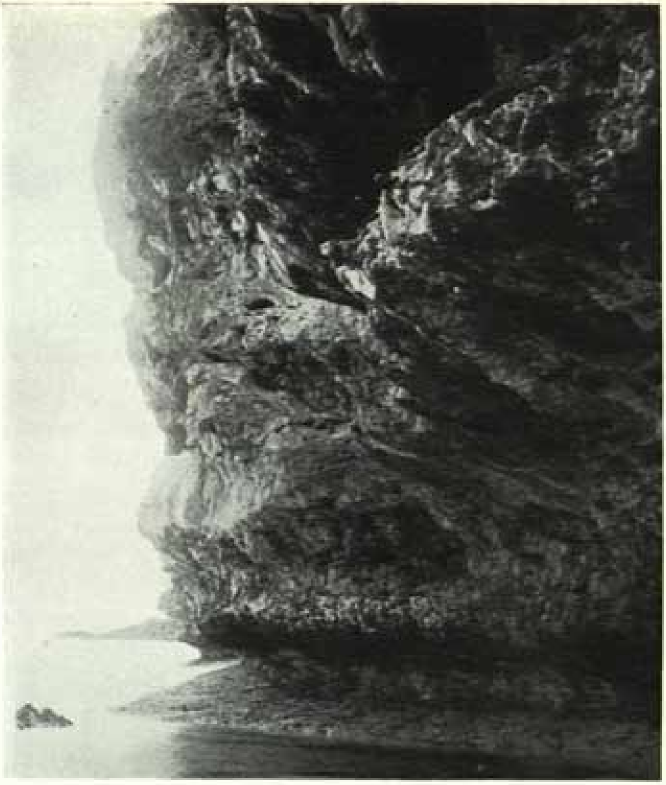

Plate 8. Five levels of erosion, Vatu Lele, Fiji
This plate shows the progressive undercutting of a limestone cliff as the land has risen relative to the level of the sea.

Plate 9. Cliffs, northern Kauai
The cliffs have been cut into the emerged wave-cut platform.

Plate 10. Akamaru island, Mangareva

Akamaru, with the island of Makapu (in the foreground), forms the western rim of the former Akamaru-Makapu crater.

Plate 11. Halemaumau crater, Hawaii

This photograph of the interior of the crater was taken on 20 September 1921. In the foreground is the crust on the north pool of the main lake. The crust is breaking up into individual blocks and sinking beneath the surface of the liquid lava. The crags are old overflow platforms inside the crater which have been lifted and tilted by the molten mass.

ACTIVE AND EXTINCT VOLCANOES

The boundary of the Pacific is commonly spoken of as a 'ring of fire', and a map showing the distribution of the volcanoes which have been active in historic times demonstrates this ring (Fig. 8). Comparison with Fig. 2 shows that the andesite line or border of the Pacific basin where it departs from the ocean border is also a zone of activity. Within the basin most of the volcanoes have long been extinct. Since the entry of Europeans into the Pacific area activity has occurred in the Hawaiian islands, the Marianas, Samoa, New Guinea, the Solomons, the New Hebrides, Tonga, and the Galápagos. Submarine eruptions have been reported from the neighbourhood of Juan Fernández, from between Laysan and Kauai (Hawaiian islands), and from lat. 7° 30′ S, long. 83° 30′ W (see list on p. 29 for details of eruptions). The Hawaiian Volcano Research Association was founded in 1911 for the study of volcanoes in and around the Pacific. There is a research laboratory in Hawaii National Park, and under the auspices of the University of Hawaii an illustrated quarterly publication, *The Volcano Letter*, is issued. It deals with volcanoes and other related topics in a manner intelligible to the layman. (For details of the Observatory on the edge of Kilauea crater, Hawaii, see vol. II, p. 303.) It is estimated that since the fifteenth century about 2.2 cubic miles of lava, besides great amounts of ash and other fragmental deposits, have been extruded in the Pacific basin. This production for so great an area is insignificant, and it is small compared with that of the boundary zones. From 1895 to 1913, 90% of the explosive eruptions of the Pacific area were in the border region (i.e., eruptions other than lava flows, or lava flows with ash deposition). Since A.D. 1500, as shown by a census made by workers at the Kilauea Observatory, 57 major volcanoes of the world have erupted 98 times and 190,000 people have lost their lives as a result. Casualties in the whole Pacific area have been less than in the more densely peopled East and West Indies. In the Indo-Atlantic half of the world there are approximately 94 active volcanoes, but for the Pacific half the figure is 336.

A comparison of Figs. 6 and 8 reveals that the frequency of volcanoes is often greatest in the neighbourhood of the ocean deeps. This is true, for example, in Japan and along the Andean coast of South America. In the andesite zone a south-west to north-east line of volcanoes with its terminal points at Ruapehu (New Zealand) and Fonualei (Tonga) lies to the west of the Kermadec-Tonga deep.

The Tonga deep bends north-westward as it points toward Suva, and the line of volcanoes which includes Niuafo'ou (Tonga) bends with it. The list of volcanic eruptions includes records from the Marianas. These islands are the summits of a submarine ridge with a basement of andesite and quartz-trachyte, and here again a trench more than 3,281 fathoms deep lies against the convex eastern side of the ridge.

The New Guinea area has already been cited as one in which great earth movements have occurred relatively recently. Five lines of volcanoes, each associated with fractures in the earth's crust, have been identified here. The first line includes the Schouten islands. The second reaches through the islands lying off the north coast of New Guinea and includes Manam, Karkar, Bagabag, the Crown and Long islands, Umboi and Tangi (New Britain). Branching off the second arc lies the third line running from Tolokiwa through Sakar, the Ritter islands, Talawe (New Britain), Langila and Bula, to the extinct volcano mount Schrader. The fourth has been called the Vitu alinement, and the fifth branches off from New Ireland into the Solomons and New Hebrides. In northern New Britain a line which includes several of the active volcanoes listed on p. 30 is to be found in the Willaumez peninsula and around Kimbe bay. It terminates in the east in Ulawun.

The individual volcanoes, active and extinct, are described in the detailed accounts of the islands in vols. II–IV. Even where activity has been long extinct and erosive forces have attacked the volcanic piles, the sites of cones and crater hollows can usually be deciphered from the remnants. A striking feature is the great number of calderas—or abnormally large craters, several miles in diameter—some occupied by lakes, others at sea-level breached to form characteristic circular bays (Plate 10). It used to be thought that these calderas had been formed by colossal explosions whereby the tops of large cones had been blown right away. (In 1937 publicity was given to a seaman's yarn that the peak of Krakatau was blown for 800 miles in the great eruption of 1883, to form an island in the Indian ocean where it fell.) Further study, and especially the evidence provided by the formation in 1883 of a caldera at Krakatau, makes it more likely that these huge craters were formed by subsidence. With a great eruption, rock is 'cored' from the walls of the volcanic chimney by the friction of the escaping material shot out from beneath. Expulsion of liquid from the subterranean reservoir leaves a cavity, and the central part of the cone collapses

into this and into the enlarged chimney. Subsequently with renewed activity new cones may arise on the caldera floor (Fig. 9). The dying stages of activity in individual volcanoes, as represented by hot springs, geysers, boiling mud and water, are well represented in the Pacific, notably in Hawaii and in the north-east of New

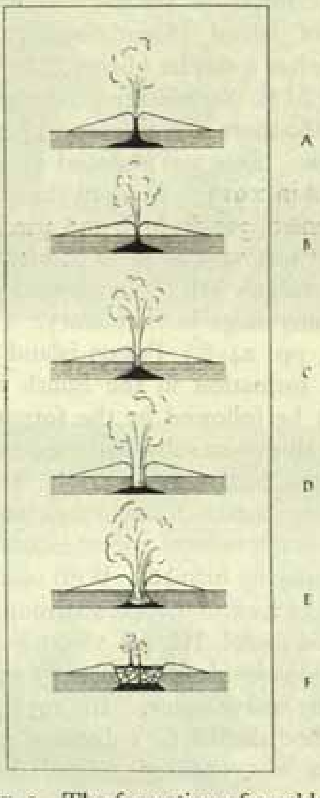

Fig. 9. The formation of a caldera

A hypothetical reconstruction showing the progressive expulsion of the magma (black) as ash, with concomitant widening of the volcanic pipe (C, D and E), and the final collapse with later extrusion of lava on the caldera floor (F). Based on Van Bemmelen, *Het Caldera Problem*, p. 21 (Batavia, 1929).

Guinea. Plate 12 shows a steam-blast eruption in Hawaii in 1924, and Plate 14 the lava spatter resulting from an eruption in 1923.

Most of the islands of the Pacific basin were formed in Tertiary times. The Hawaiian islands are largely built up of fluid lavas

which well up from the craters (i.e., 'shield' volcano activity, Plate 11), whilst fragmental products predominate in the islands of the south-west Pacific. (For *pahoehoe* (smooth) and *aa* (rough) lavas in Hawaii, see Plates 13, 15, and vol. II, p. 304 and Plate 61.) The birth of a volcanic island has been witnessed in recent times in the formation of Fonuafo'ou (Falcon island), Tonga, and its history is that of a swaying struggle between the forces of volcanic accumulation and marine destruction. Bogoslof island (Aleutians), which seems to have appeared about 1768, has a similar history. In 1865 H.M.S. *Falcon* reported a shoal. H.M.S. *Sappho* reported smoke issuing from this shoal in 1877. In 1889 there was an island 1¼ miles long and 1 mile wide and 153 ft. high. This was reduced to a shoal by 1898, and was a submarine bank in 1913. In 1927 the volcano again erupted and an island was formed, 300 ft. high and 3 miles in circumference. In November 1940, it was only 20 to 30 ft. high. It was composed of cinders and loose volcanic ash. No growing coral has been found on Falcon island at any stage in its history. (For a more detailed account see vol. III, pp. 24–8.) Falcon island may be regarded as at stage 1 of island formation in the South Seas. Extinction of volcanic activity may be followed by the formation of a submarine bank—stage 2. If at this point subsidence occurs, submarine deposits will accumulate on the bank—stage 3. If the bank is below the depth of reef-building corals, foraminifera and algæ will be the important limestone builders until a level is attained at which corals can live and an atoll may be formed. With uplift a limestone island —stage 4—will result. ('Eua, in the Tonga group, which is an example of stage 4, is described in vol. III, pp. 18–21.)

Where upheaval and volcanic action occur together, major changes in coastal topography may occur. In 1913, in Ambrim (New Hebrides), the coastline shifted to a distance of one mile, and the whole coastal region was uplifted several feet. Compensating subsidence occurred in other parts of the region. The volcanoes involved were mounts Benbow and Marum.

Volcanic Activity Recorded since the Sixteenth Century

The following Table gives a list of known outbreaks from the sixteenth century, so far as records are accessible, but it is not necessarily complete.

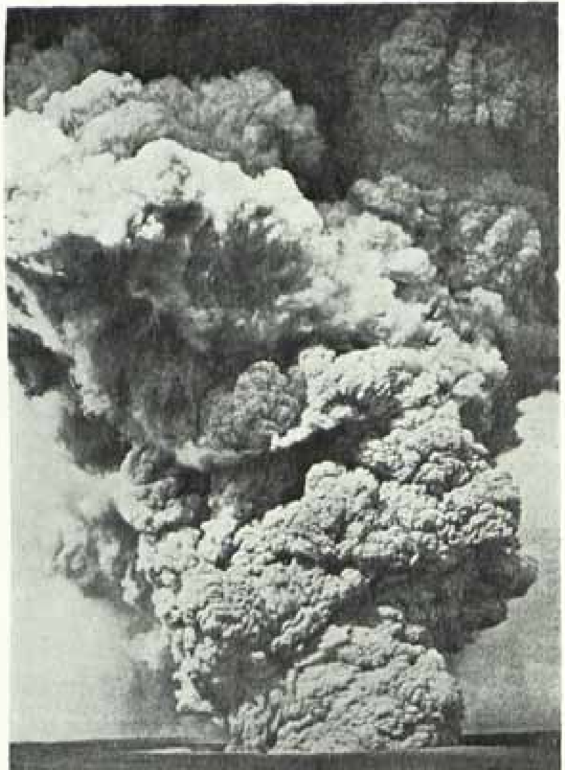

Plate 12. Steam blast eruption, Halemaumau

This photograph was taken about 0830 hr., 22 May 1924. Note the tendency towards a spiral vortex in the dark, electrically charged cloud above.

Plate 13. Toes of *pahoehoe* lava

This lava was erupted in 1919 on to the north floor of Kilauea crater, Hawaii.

Plate 14. Lava spatter, Hawaii
The after-effects of an eruption on 25 August 1923, west of Makaopuhi. The lava spatter is seen in the trees. There is a deposit of sulphur along the flow-crack in the forest.

Plate 15. Typical *pahoehoe* surface
A lava flow from the south-west flank of Kilauea, December 1919. The skin of vesicular glass, which forms rapidly, is often crinkled and contorted.

Juan Fernández Area

Submarine outbreaks are as follows:

1. One mile off Punta Bacalao (1835).
2. After a seaquake several islands formed at 33° 34′ S, 76° 49′ W; at 33° 40′ S, 76° 49′ W; and at 33° 20′ S, 78° 20′ W (1839).
3. After a seaquake in 34° 55′ S, 77° 38′ W, dead fish came to the surface and the sea water was observed to be of milky colour (1867).

Galápagos

1. On Fernandina four volcanoes were active in 1813, and two in 1814. Lava flows were observed in 1825. Eruptions were recorded in 1928, and in the south of the island in 1937.
2. On Isabela activity was observed in 1797, 1800, 1813, 1835, and 1844. In April, 1925, lava flowed into the sea on the northern coast. There was an eruption south of cape Berkeley in 1928.
3. On Floreana there were eruptions in 1813 in the centre and in 1897 in the south of the island.
4. On San Salvador there was activity in 1899.
5. An isolated submarine outbreak has occurred in 83° 20′ W, 7° 30′ S.

Hawaiian Islands

1. Haleakala (Maui) last erupted about 1750.
2. Hualalai (Hawaii) last erupted in 1800–1.
3. Mauna Loa last erupted in 1943, and erupts on an average every $4\frac{1}{2}$ years.
4. Kilauea is almost continuously eruptive.

Submarine outbreaks:

1. Liquid rock (magma) withdrawing from Kilauea in 1868 appeared on the ocean floor.
2. In 1877 there was an eruption in Kealakekua bay due west of the summit of Mauna Loa.
3. In 1880 there was a pumice outbreak off the north-east coast of Hawaii.
4. In 1906 what was probably a pumice outbreak occurred between Laysan and Kauai.
5. In 1850 an isolated submarine outbreak was recorded in 20° 56′ N, 134° 35′ E.

Marianas

Dates of eruptions here are as follows:

1. Uracas (Farallon de Pajaros) in 1865, 1875, 1901 and 1912.
2. Guguan in 1901.
3. Pagan in 1922.
4. Asuncion island in 1906.
5. In 1846 a great floating pumice area, possibly from the Marianas, appeared in 16° N, 125° E.

Islands off the North-east Coast of New Guinea

Eruptions have been recorded in the Schouten islands at:

1. Blupblup (Garnot) in 1616.
2. Kadovar (Blosseville) in 1616 and 1700.
3. Bam (Lesson) in 1616, 1909 and 1919.

Other eruptions in the islands off New Guinea were:

1. Manam in 1616, 1643, 1845, 1877, 1887, 1889, 1895, 1902, 1910, 1917, 1919, 1921, 1936, and 1937.
2. Karkar in 1643 and 1895.
3. The eruptions in the south-east of New Guinea are little known, but there are indications of recent activity in the areas around mounts Victory and Trafalgar.
4. The Ritter islands in Dampier strait had eruptions in 1700, 1793, 1887 and 1888.

North Coast of New Britain

1. Tangi and Talawe were active shortly before 1890.
2. Pago (Bango) was active between 1900 and 1910, and in 1912.
3. Langila was active between 1900 and 1910.
4. In the Willaumez peninsula mount Banda erupted about 1910 and Bula is semi-active.
5. Ulawun (The Father) erupted in 1770, 1912, 1915 and 1937.
6. Bamus (The South Son) was active in 1899 and 1912.
7. In Lolobau island (Namisko) there was an eruption in 1905.
8. Tavurvur (Matupi) erupted in 1767, 1791, 1878, 1937 and 1941.
9. At Sulphur creek there was activity about 1850.
10. A submarine outbreak occurred off Rabaul, in Blanche bay, in 1878. Volcano island was formed then. In 1937 there was a serious eruption off the Rabaul area, coinciding with that of Matupi, which lies on the south-east side of Blanche bay.

Solomon Islands

1. On Bougainville island, Bagana erupted in 1874, a few years before 1900, in 1908 and in 1938.
2. Mendaña reported an eruption on Savo in 1568, and later ones occurred in 1820 and 1850.

Santa Cruz—New Hebrides

Eruptions have been reported as follows:

1. Tinakula in 1595, 1767, 1797, 1869, 1871, 1886 and 1909.
2. Vanua Lava in 1856 and 1861.
3. Mounts Benbow and Marum (Ambrim) in 1863, 1864, 1871, 1888, 1894, 1908, 1912, 1913, 1929 and 1937.
4. Lopevi, in 1863, 1864, 1884, and several times since then, the latest being in 1939.
5. Yasur (Tana) is almost continuously active.
6. Hunter (Fearn) island in 1841, 1895 and 1903.

Submarine outbreaks:

1. Between Epi and Tongoa in 1897 and 1901.
2. Between Traitor's Head (Eromanga) and High rock in 1881.

Samoa

1. In Savai'i there was a lava flow in the north-west in 1700. Two new parasitic cones were formed to the north of Maunga Afi in 1760. In 1902 a second crater formed in the west.
2. At Matavanu activity lasted from 1905 to 1911 (Plate 16).
3. There was a submarine outbreak in 1866 near Olosenga in 14° 13′ S, 169° 34′ W.

Tonga Area

Eruptions have been recorded as follows:

1. Niuafo'ou about 1814, in 1853, 1867, 1886, 1887, 1912, 1923, 1929, 1935 and 1943.
2. Fonualei in 1791, 1847, 1897, 1937, 1938, 1939.
3. Late island in 1790 and 1854.
4. Metis shoal was formed in 1858. In 1878 it was an islet 110ft. high. It was still active in 1886, but it was 2 fathoms below sea-level in 1898.
5. Tofua in 1774, 1792, 1854, 1900 and 1906.
6. Falcon island (Fonuafo'ou) was last reported to be in eruption in 1936.

Submarine outbreaks in this area occurred:

1. In 1874, between Ha'apai and Tongatapu.
2. In 1907, in 21° 27′ s, 175° 47′ w.
3. In 1911, in 20° 50′ s, 175° 33′ w.
4. In 1912, two miles south-east of Hunga Ha'apai.
5. In 1928, a pumice eruption in 17° 25′ s, 176° 09′ w.
6. In 1932, thirty miles south-west of the west end of Tongatapu.
7. In 1939, about one mile south-east of Niuafo'ou.

Kermadec Area

1. An island arose in Denham bay in 1870–72, and disappeared in 1877. There was an outbreak in the central crater in 1872.
2. Curtis island had an eruption in 1899.

Submarine outbreaks occurred in the area:

1. In 1825, in 30° 14′ s, 178° 55′ w.
2. In 1870, near Raoul island, in 29° 14′ s, 177° 55′ w.
3. In 1886, in 29° 11′ s, 177° 52′ w.

EARTHQUAKES

An earthquake is a shaking of the ground and in comparatively rare instances is associated with a permanent displacement of a few feet. The movement is in a vertical or horizontal direction or both. The place beneath the surface where the shock originates is called the focus, and the position at the surface vertically above this is the epicentre. According to depth of focus earthquakes are classified as:

Normal—focus less than 40 miles down (commonly 6 to 10 miles).

Intermediate—focus from 40 to 150 miles down.

Deep—focus from 150 to 450 miles down.

Fig. 10 shows the distribution of the Pacific regions which are especially subject to earthquakes. The main feature is a belt almost completely encircling the Pacific basin with an arm running from southern Chile to Easter island, and then 2,600 miles to the south-west. At its nearest point this arm is separated from the western part of the belt by 1,800 miles. All the great deeps occur within the belt.

The great majority of Pacific earthquakes have foci at normal depth. Some are definitely related to volcanic activity and give evidence of movement of rock liquid within the crust. Others are due to sudden displacements along fractures in the solid crust;

intermediate and deep ones are probably all of this type. The earthquakes of the Hawaiian islands are chiefly due to volcanic activity. Those occurring in 1929 in the area around the volcano of Hualala, are thought to have resulted from movement of magma (molten rock)

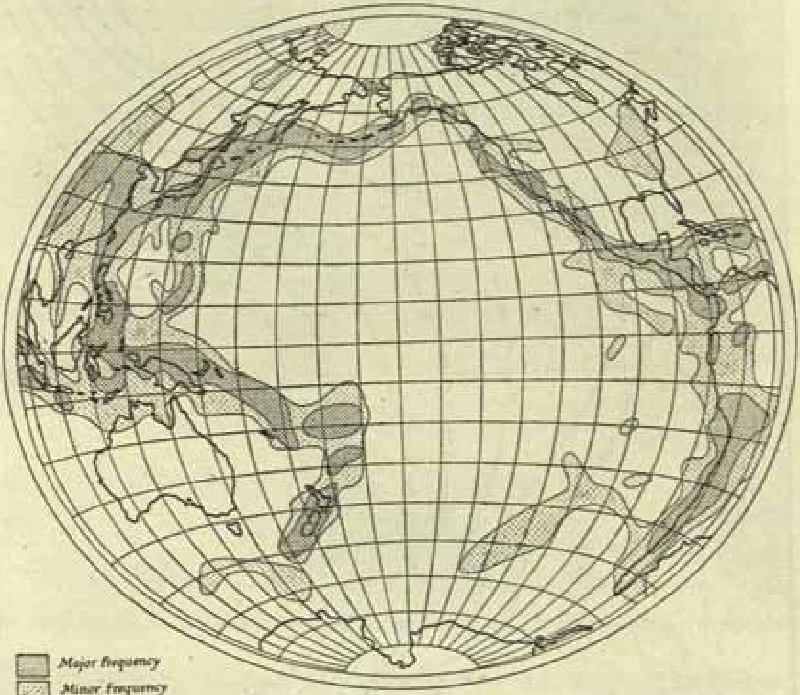

Fig. 10. Earthquake belts of the Pacific ocean

The areas of occurrence of earthquakes are shaded according to frequency. This map may be compared with Fig. 8. Based on N.-H. Heck, *Earthquakes*, p. 110 (Princeton and London, 1936).

which passed into Hualalai from beneath Mauna Loa (vol. II, p. 302). There have, however, been strong shocks, notably in 1868 and in 1929, which may have been of deeper origin. To cite an example of permanent displacement, destructive shocks occurred in the vicinity of Kapoho, the east point of the island of Hawaii in 1924. A block of land subsided by amounts of up to as much as 11 ft., and a new lagoon 100 yd. across was formed with coconut palms standing in 8 ft. of water. In the northern Pacific belt where horizontal displacements have taken place (in California, Japan and the Philippines), the continental sides have moved southwards

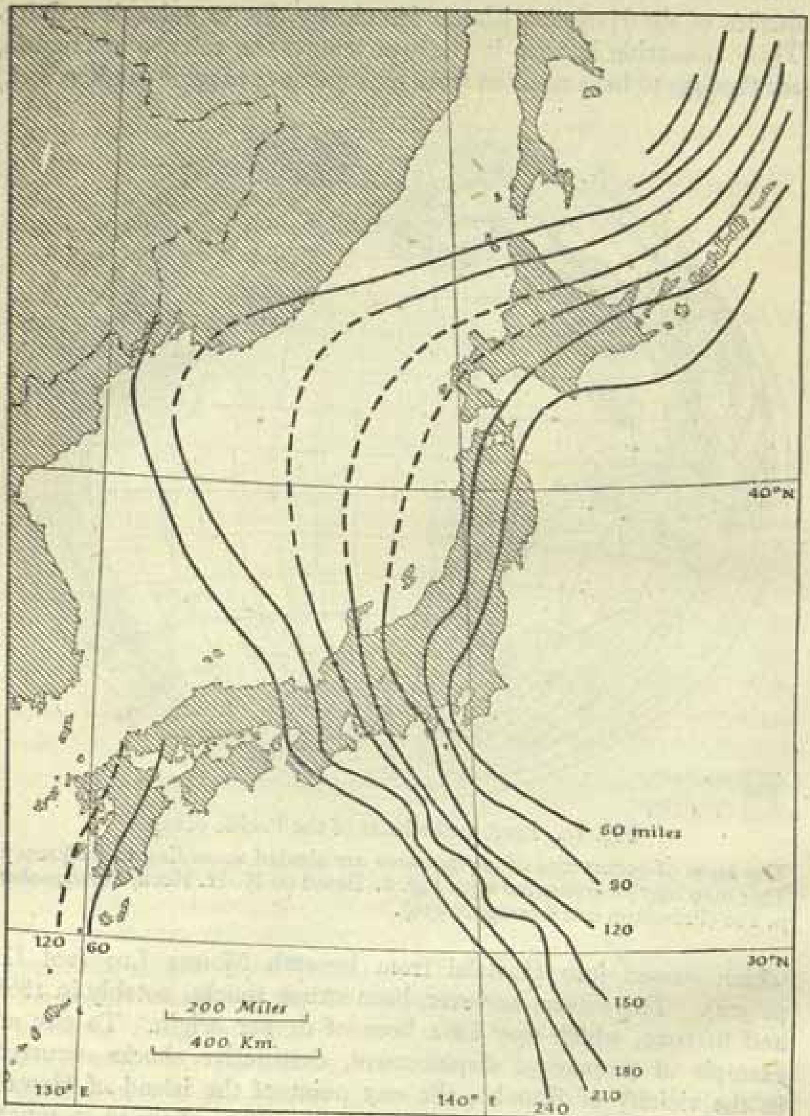

Fig. 11. Increase in depth of earthquake foci towards the Asiatic continent

Each heavy line is drawn through the epicentres of earthquakes at equal focal depths. In the absence of seismic records the broken lines are inferential. Based on John Milne, *Earthquakes and other Earth Movements*, p. 154 (new edition by A. W. Lee, London, 1939).

relatively to the Pacific side, but more observations are needed before this can be regarded as a rule.

Special interest attaches to the deep earthquakes. Apart from the East Indies they are known only in the circum-Pacific area. The foci of all earthquakes deeper than 200 miles occur close to and on the continental side of the boundary of the ocean, although the alinement of the epicentres is not everywhere strictly parallel to the boundary, as may be seen from Fig. 11. A detailed study of the evidence leads to the conception (illustrated in Fig. 12) that the continental part of the crust is riding up over the oceanic, and the oceanic is thrusting under the continental along great fracture planes inclined away from the ocean at an angle of about 20° and extending to depths of hundreds of miles. Volcanoes are commonly found where the fracture is at a depth of about 60 miles, whilst normal

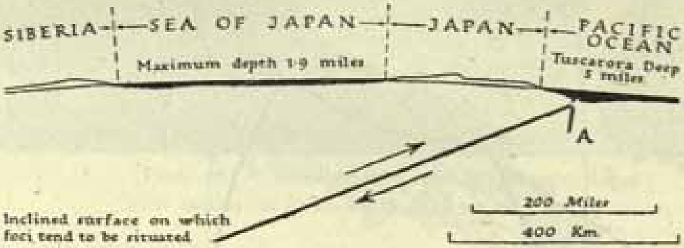

Fig. 12. Distribution of earthquake foci along an east-to-west section through Japan

The line A indicates the range of depths of normal earthquakes. The oblique line drawn from the same point represents a great fracture-plane in the earth's crust; the continental part of the crust (west of the plane) is riding up over the oceanic part (east of the plane). This earth movement gives rise to earthquakes with foci situated on this plane. Based on John Milne, *Earthquakes and other Earth Movements*, p. 179 (new edition by A. W. Lee, London, 1939).

earthquakes with shallow foci occur where the fracture approaches the surface. Fig. 13 shows the alinement of the volcanic rifts of Japan.

Using very sensitive 'tiltmeters' it has been shown in Japan that volcanic eruptions and earthquakes are preceded for years by tilting of the ground, but the time and precise location of coming shock cannot be predicted. There is no doubt that there will be great earthquakes round the Pacific during each coming year. There is no day without small shocks. There need not be any excessive damage, for earthquake-resistant structures can be built at a cost

not much exceeding that of ordinary buildings. All works of construction in the circum-Pacific belt should be made earthquake-proof.

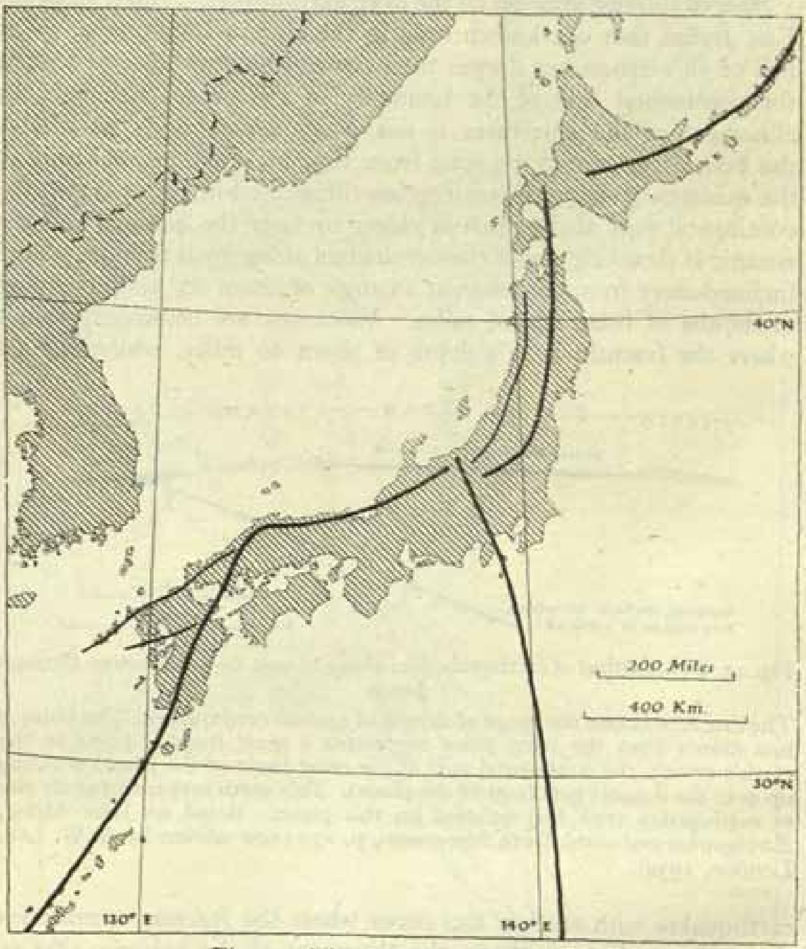

Fig. 13. The volcanic rifts of Japan

The heavy lines indicate the positions of volcanic rifts and their convergence in the central highlands of Honshu. Based on *The Volcano Letter*, no. 323, p. 14 (Hawaiian Volcano Observatory, National Park, Hawaii, 1931).

Seismic Sea Waves

Earthquakes accompanied by vertical displacement of the sea bottom give rise to sea waves which can be detected over the whole Pacific and may cause disasters when they reach shelving shores and flood

Plate 16. Contact explosion, Matavanu, Savai'i
This explosion followed the fall of lava into the sea.

Plate 17. The eastern face of Mangareva
This view is taken through a gap in the narrow eastern barrier reef. The peak in the distance is mount Duff. The gap in the reef is choked with coral sand washed in from the lagoon.

Plate 18. The wreck of the German warship *Adler*
This shows one of the three German warships which, with three American warships, were driven ashore at Apia in 1889 during a violent hurricane.

Plate 19. Wreckage in the Wailoa creek, Hilo
This photograph was taken on 3 February 1923. A tunami had occurred seven hours earlier, after an Aleutian earthquake. Sampans were thrown over the railway bridge at Waiakea station, which was destroyed.

low coastal lands. These seismic sea waves or *tunami* (from Japanese *tu*, a port, and *nami*, a long wave) have been called tidal waves for so long a time that the term will probably persist in everyday English despite the fact that such waves, which may also result from submarine volcanic eruptions, landslips, and cyclones, are in no way related to the tides. Their effects on shipping may be as disastrous as those produced by hurricanes (Plates 18, 19).

In the neighbourhood of the epicentre the effect may be such that the navigator thinks that he has struck a rock. Loose objects may be overturned, bolts and rivets started, and even masts broken. Although the vessel may not be directly over the epicentre the vibrations appear to come from directly underneath. Despite its slight compressibility a mass of water responds as an elastic body to the short-period oscillations of submarine earthquakes, and the vibrations travel towards the sea surface with a velocity equal to that of sound. Such experiences have given rise to the insertion on old charts of some of the numerous shoals and reefs which modern research has shown to be non-existent. The elastic waves may cause fatal damage to the air bladders of fish. Generally fish are caught only with great difficulty a few days before a great seaquake: perhaps they are sensible to the weak fore-shocks which precede great earthquakes. Some kinds of fish on being frightened by a shock swim about in great shoals apparently looking for a place of safety; other kinds migrate to centres of seismic activity, seemingly attracted to such places.

It is the transverse sea waves which may be so formidable. In the open sea they are unnoticeable, being about 100 miles from crest to crest and only a few feet in height. In shallow water the amplitude increases. Strong currents may be set up which mystify the navigator. This may happen even with a comparatively small tunami on approaching the land, especially if there are narrow channels in the direction of its progress. The greatest wave heights are experienced at shelving shores and particularly at the heads of V-shaped bays. The advent of a large tunami is commonly (though not always) heralded by a slow withdrawal of the water, followed by an advancing wall—the most spectacular and appalling of all earthquake phenomena. There may be a series of waves and a later one may be more destructive than the first. In 1896 an earthquake with its epicentre at 4,600 fathoms in the Tuscarora deep caused a tunami which swept the coast lands of Sanriku, Japan, reaching a height of 100 ft. About 2,700 people were killed, and hundreds

of vessels of various kinds were left lining the foothills. The danger to the populations of low coral islands is great. A European in the Fiji group in May 1877, for instance, recorded 'a terrible wave which swept away thousands of the inhabitants of the atoll islands'.

Tunami arriving from great distances may be unnoticed ashore but be marked on the record of the automatic tide gauge. Tunami originating off the coasts of Chile, Japan, and the Aleutians have damaged craft in the harbour of Hilo, Hawaii (Plate 19). When a distant earthquake is recorded on the seismograph on Hawaii and there is a possibility that it was a submarine shock, warnings are issued to the harbour master. From the time elapsing between the arrival of the primary and secondary earth waves the distance away of the epicentre can be determined, and, knowing the velocity of the sea waves, which in the Pacific is about 450 miles per hour, the time of arrival can be predicted. As this is not for some hours after the earth shake from a great distance there is ample time to take precautions. Two examples may be cited.

On 3 October 1931, a distant earthquake was recorded at Hawaii. The secondary earth wave arrived 7½ minutes after the primary one and this interval was found from tables to indicate an epicentre 3,680 miles away. From the direction of the disturbance of the seismograph pendulums the epicentre was deduced to lie either to the north-east or the south-west. If to the north-east it would have been in North America and therefore there would be no water wave. If to the south-west, it would have been off New Caledonia. But as there are many island chains in that direction it was decided that the wave would probably be damped out by the shielding action of the islands, and no warning was given. This was justified by the events. At the expected time the water in Hilo bay began to rise and fall half a foot every 15 minutes, and continued to oscillate with slowly decreasing amplitude for two days. Subsequent reports revealed that the earthquake had occurred in the neighbourhood of the Solomon islands. Some tunami last for a few hours and the long cont nuance of others may be due to reflection from coasts near the epicentre, or waves may be broken up into many small ones by passing through groups of islands. Also, large bodies of water in bays will vibrate in their natural periods ('*seiche*' oscillations) long after being disturbed.

On 2 March 1933, a strong earthquake was recorded on Hawaii, indicating an epicentre 3,950 miles away. Warnings were issued of a wave to be expected in 8½ hours. The sampan fleet was moved

out to harbour anchorages, and stores were removed from wharves. The wave, which originated in the Tuscarora deep, arrived within 6 minutes of the predicted time. It had a range of 17½ ft. in a series of ten-minute interval swings. Wide tracts of the sea bottom were bared and much damage resulted from the flooding of houses.

Submarine earthquakes have broken telegraph cables. In 1888, three cables connecting Australia with Java fractured simultaneously, and in the supposition that this sudden isolation indicated an act of war the Australian naval and military reserves were called out.

CORAL REEFS

The Pacific islands—often classified into two types, the 'high' volcanic and the 'low' coral—show a great development of living coral reefs (Fig. 2). A growing reef is a shallow-water tropical community of lime-secreting organisms, mainly corals with foraminifera and mollusca (animals), together with nullipores (plants) which latter have an important influence in cementing the whole deposit. The red seaweed *Lithothamnium* is particularly effective in cementing the outer surf and wave-battered edge of the reef, where it may build a 'lithothamnium ridge' up to a few feet high. The upward rate of growth of a vigorous reef is estimated to average 1½ in. a year.

Reef-building corals do not grow at lower temperatures than 68°F.; those which will thrive at a certain temperature will barely survive a fall of only a few degrees. Speed and solidity of growth is greatly affected by light; in absence of light there is a slowing down of growth and weaker skeletons are formed. The animals are highly specialized for getting rid of mud, but rapid sedimentation will kill them. They cannot survive long exposure to the air, and they require water of normal marine salinity. The most favourable depth for healthy coral development is 15 ft.—i.e., most vigorous growth takes place immediately below the disturbed surface water. Growth does not occur below about 200 ft., probably because of the lack of light. The areal distribution of the living reefs is governed by the surface temperature of the ocean and they are not found towards the eastern borders, because of the cold sea currents and upwelling of cold water there.

Three main types of reef are recognized: fringing, barrier, and atoll. (Examples are shown in section on Fig. 14.)

The *fringing reef* is a flat extending outwards from the high-tide

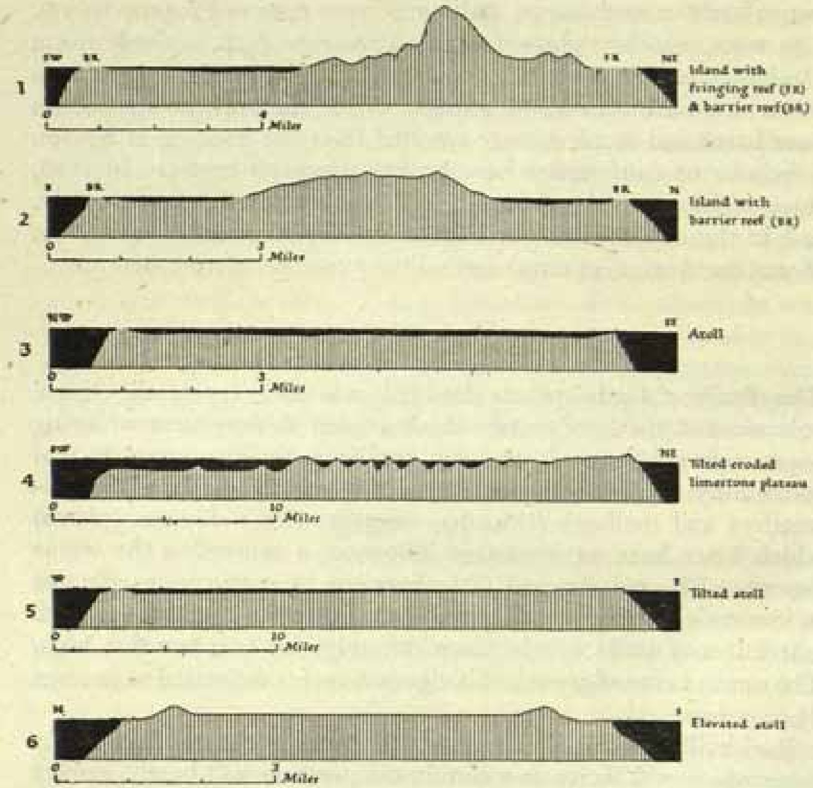

Fig. 14. Reef sections

Each section (1–6) represents a cross-section of an actual island with its reefs. The vertical scale has been exaggerated as follows: 1—Ngau (Fiji), twice; 2—Nairai (Fiji), 3 times; 3—Funafuti (Ellice islands), 3 times; 4—Vava'u cluster (Tonga), 7 times; 5—Uvea (Loyalty islands), 7 times; 6—Kambara (Fiji), 3 times. Section 1 is based on A. Agassiz, 'The Islands and Coral Reefs of Fiji', *Bulletin of the Museum of Comparative Zoölogy at Harvard College*, vol. XXXIII, plate 13 (Cambridge, Mass., 1899). The others are based on R. A. Daly, *The Changing World of the Ice Age*, pp. 221, 251, 246, 246 and 245 (New Haven, 1935).

shore-line, with some scattered living coral colonies, but the region of active growth and of extensions is at the seaward edge and in the bordering shallows. Large blocks of coral rock with a thin blackened coating of algal growth (formerly colloquially known as 'niggerheads') may be found on the flat. These blocks, which are sometimes mistaken for volcanic rock, have been torn from the seaward edge and carried forward by great waves raised by tropical cyclones or, less

commonly, by volcanic eruptions and tunami. The reefs may be over a mile in width but they are commonly narrower. They are well developed in situations facing winds and currents which bring food and clear water conditions, whereas they are absent at river mouths where the falling sediment, diminished illumination, and brackish water are inimical to life. The extension of the reef into deep water can take place only with the building up of a talus bank to the level at which the corals can live.

The *barrier reef* (Plates 17, 20–2) is a similar flat, 20 to 1,000 ft. or more in width, roughly parallel to the shore, and separated from it by a lagoon (or 'moat' as Darwin called it), commonly from ½ mile to 10 miles or more in breadth. The most striking example, the Great Barrier Reef of Australia, is 600 miles long, approximately 50 miles off-shore, with a lagoon averaging 100 ft. in depth. The lagoons of some barrier reefs are so little occupied by an island or islands that the reefs are known as 'almost-atolls'.

An *atoll* (Plate 24) is an almost continuous reef, enclosing a flat-floored lagoon commonly 30 to 100 ft. deep, with a maximum depth of 300 ft. (Plate 25). Some atolls are nearly circular. The outward slopes to deep water are steep, commonly about 40°—one of 50° down to 2,000 ft. is known. The atolls are commonly separated by deep water. There are fifty in the Tuamotu islands with no inter-atoll depth less than 3,000 ft. and many exceeding 12,000 ft. Atolls may lie on ridges like chimney pots on a roof or on flats like barnacles. Drowned atoll reefs are known, e.g., the Penguin and Alexa banks north of Fiji. Some atolls may be coral cappings on submerged caldera rings; if so, they are exceptional.

Old fringing reefs now above high tide level are found on many islands. Those at elevations up to 15 ft. are common and they probably owe their situation to a recent fall of sea-level. Some higher

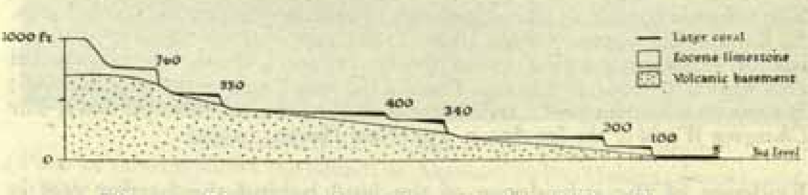

Fig. 15. Diagrammatic section, east side of 'Eua, Tonga

This section shows the terraces formed during the period of the fall of sea level. The figures give the heights of the terraces in feet above the present level. Based on J. E. Hoffmeister, 'Geology of Eua, Tonga', *Bernice P. Bishop Museum Bulletin*, no. 96 (Honolulu, 1932).

ones are due to elevation of islands. On the windward (eastern) side of 'Eua is a remarkable series of limestone platforms and cliffs at heights of 760, 550, 340, 200 and 100 ft. (Fig. 15). The terraces have been cut by marine erosion, but reefs grew at the outward edges of the 550 ft. and lower terraces. There is a 200-ft.-wide reef at 4 ft. above high tide, and a living fringing reef. On the western side of 'Eua at 400 ft. is what appears to be a raised barrier-reef flat separated from the higher land by a valley. A similar valley on Mangaia (the Taro flats), however, is believed to have been formed by erosion of the inner part of a fringing reef after elevation of the island. Many raised almost-atolls and atolls are known, at elevations up to 300 ft.—these include the important raised atoll of Nauru.

Origin of Barrier and Atoll Reefs

Charles Darwin considered these reefs to have been developed from fringing reefs as a consequence of gradual subsidence. With upward growth of the reef as the sea advances up the island slopes, and the recession of the shore line, a lagoon is formed between reef and island. Eventual submergence of the latter results in an atoll (Fig 16).

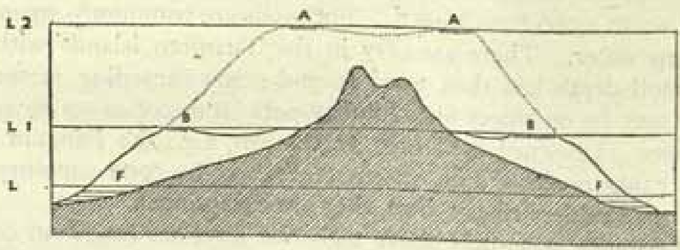

Fig. 16. Diagram illustrating Darwin's theory of the formation of coral islands by subsidence

The volcanic core of an island is shown in cross-section by the shaded area. L, L1 and L2 represent three stages in the rise of sea-level relative to the island. The accompanying upward growth of coral is shown by the unshaded area within the bounding lines. The shaded area F represents fringing reef; B represents barrier reef; and A the atoll rim. Based on R. A. Daly, *The Changing World of the Ice Age*, p. 254 (New Haven, 1935).

Evidence of the subsidence of the land behind the barrier reef is afforded by drowned river valleys, and further confirmation of subsidence has been sought by making borings into the reefs. If the coral is thicker than 200 ft. (the only range within which the corals can live), this would be evidence of subsidence. A boring into the

Plates 20, 21, 22. Views in the Mangareva group

Plate 20 (above) shows the islands of Akamaru (left), Mekiro (centre), and Aukena (right); they are seen through a gap in the eastern barrier reef. Plate 21 (middle) is another view looking westwards across an islet on the eastern reef to the gap between Akamaru and Aukena; mount Duff is seen on the right. Plate 22 (below) is a view looking across the same reef from a position further north. Akamaru and Mekiro show to the left and Aukena to the right.

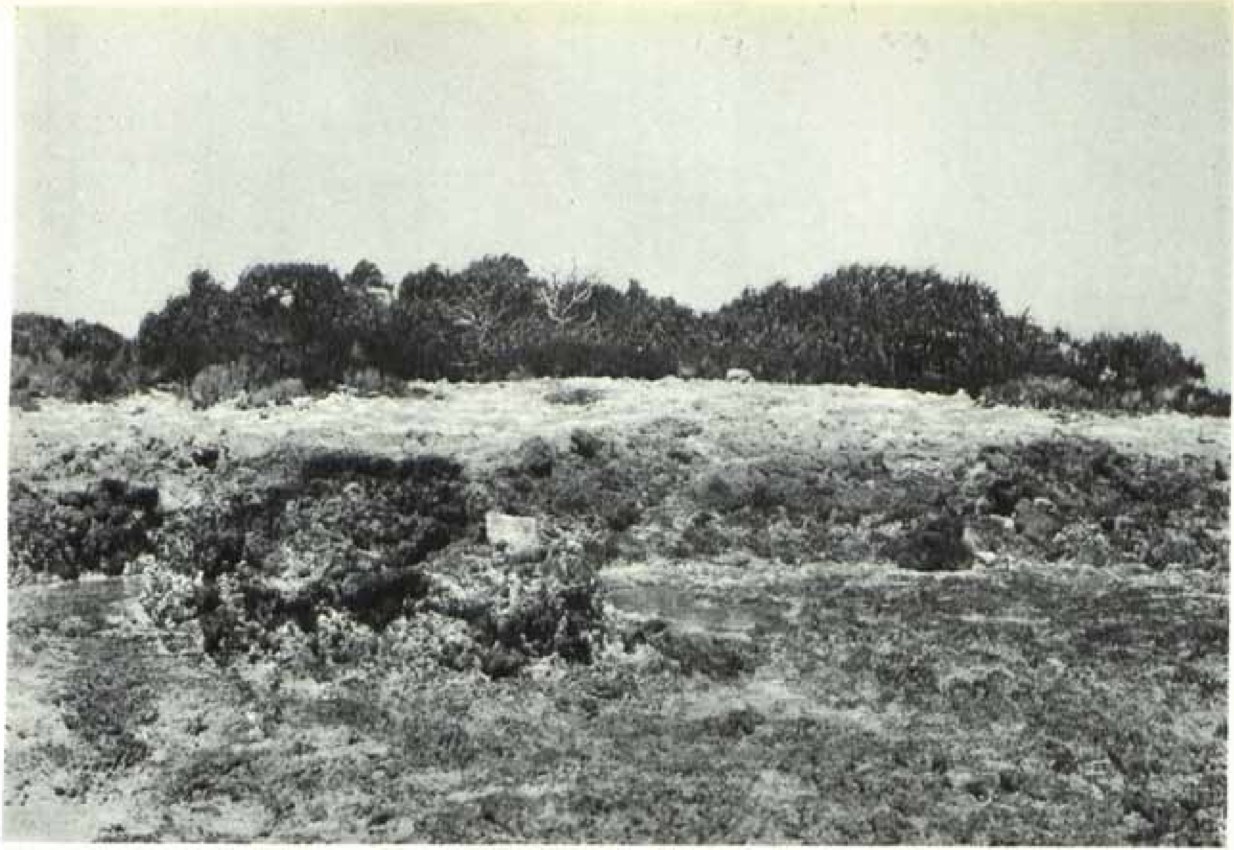

Plate 23. A section of beach, Mangareva

This view shows the line of demarcation between the outer reef flat and the eroded face of the old land line at the base of a dam of loose coral rubble.

Funafuti atoll reef showed a thickness of 1,114 ft. of coral limestone, while a boring into the lagoon floor showed 282 ft.—in both cases no base to the coral rock was reached. It is considered that the lower part of the rock passed through in the deeper boring is probably coral talus, which accumulates on the seaward side of atolls. This leaves the evidence of subsidence inconclusive, although the presence of shallow-water fossils in position of growth in the talus supports the idea of subsidence. A boring into the Great Barrier Reef of Australia proves a recent subsidence of 600 ft. Reef coral was found down to 500 ft. and below that were quartz and foraminiferal sands. In Oahu (Hawaiian islands), coral limestone interbedded with lava and ash has been found in a well at 1,034 ft. below sea-level. Also, many atolls have outer submarine slopes steeper than those of talus or of normal volcanoes—a feature which is explained by Darwin's theory.

The lagoons within barrier and atoll reefs are shallow, and show little variation of depth compared with the great depth of the ocean around them (Fig. 17). Their floors, also, are remarkably flat. As the submergence postulated by Darwin is much greater than the depth of the lagoons, and coral growth on the lagoon floor is absent or insignificant, he supposed that deposition of material washed into the lagoons from outside and eroded from the inner reef margins, being distributed evenly over the floors by the agitation of the shallow water, kept pace with the sinking of the foundations and upgrowth of the reefs. This is a reasonable explanation. But some observers have thought that in some cases a greater rate of subsidence than of lagoon infilling might have occurred, and impressed by the absence of any deep 'moats' within the reefs, they have sought hypotheses which involve no great subsidence of foundations.

In the 'glacial control theory' developed by R. A. Daly, the growth of the present reefs is considered to have been initiated at the close of the last Ice Age, and on platforms produced under the special conditions which obtained during the cold periods. During the Quaternary Ice Age (or ages, for there is evidence in continental Europe, for example, of four cold periods separated by warmer 'inter-glacial' episodes) world temperatures were lowered—a fall of about 9° F. of the temperatures of the surface Pacific waters has been estimated. Glaciers existed then on the plateau of Mauna Kea (11,500 to 13,000 ft.) on the island of Hawaii. Another consequence of the Quaternary Ice Age was a lowering of sea-level owing to the abstraction of water by evaporation and its accumulation

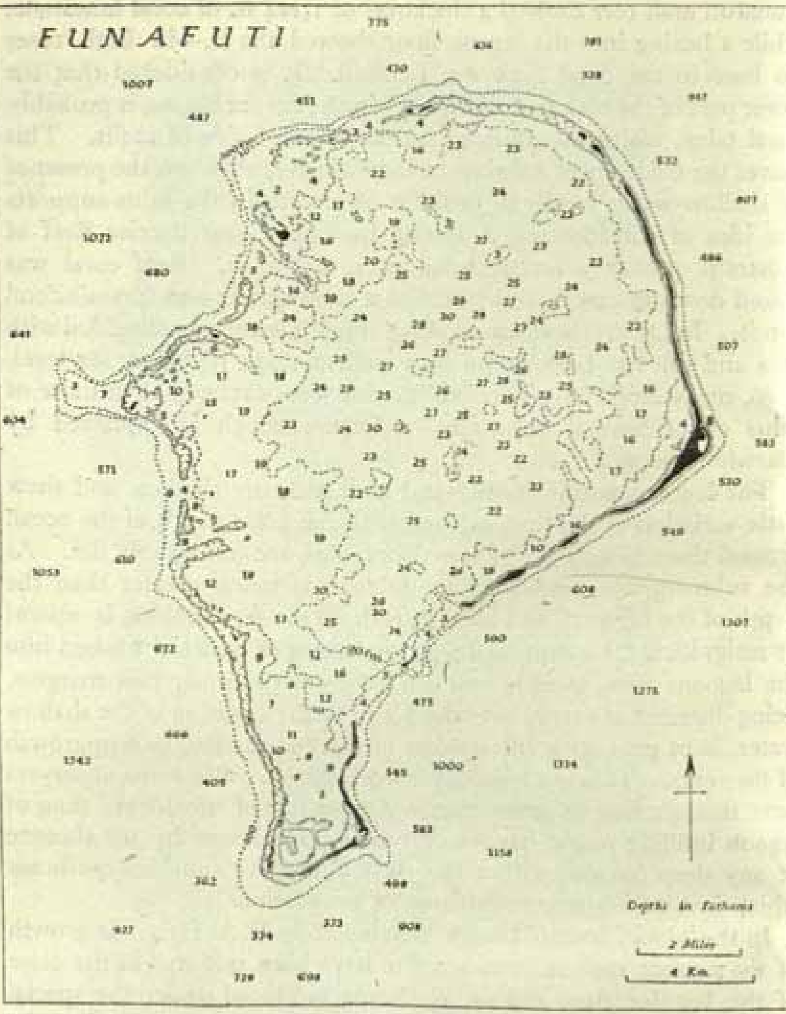

Fig. 17. Funafuti atoll

The figures indicate depths in fathoms. B (off the centre of the eastern rim) marks the site of the deepest bore-hole, which was sunk in 1897–8 to 1,114 ft. Based on: (1) Admiralty chart no. 2983; (2) R. A. Daly, *The Changing World of the Ice Age*, p. 251 (New Haven, 1935).

in the solid state to form glaciers on the lands. It is estimated that, owing to this cause, the sea-level fell by about 300 ft.

Under such conditions it is surmised that the corals would be killed off or their growth diminished by the lowering of temperature,

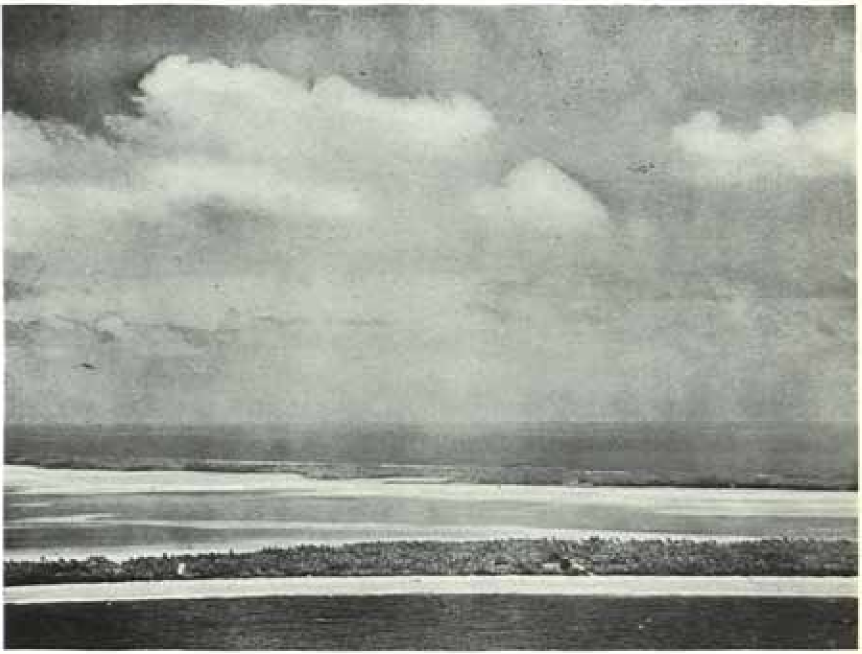

Plate 24. Tarawa atoll, Gilbert islands

An aerial photograph taken from a height of about 800 ft. Both sides of the atoll rim, covered with coconut palms, can be seen. Between them, showing lighter than the open sea, are the shallow waters of the lagoon.

Plate 25. The lagoon flat, Butaritari

This photograph shows the eastern edge of the lagoon flat on the north side of the Keuea gap. It exemplifies the gently shelving muddy beach on the lagoon side of an atoll rim.

Plate 26. Southern Kauai, Hawaiian islands
This view shows dissection of volcanic highlands.

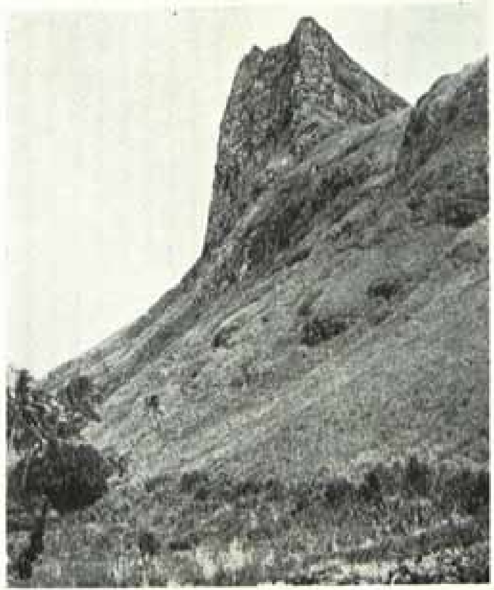

Plate 27. Mount Duff, Mangareva
This view is taken from the summit of the plateau on the south side of the peak. The mountain is a remnant of harder material left after considerable erosion of the rest of the island.

and that in the absence of a growing reef the destructive action of the waves would have full play in attacking the new shore line and would thus erode a shore platform. With the return of warmer conditions, corals spread on these platforms and, with the rising sea-level produced by the returning water from the melting glaciers, grew upward and outward, to form the present barrier reefs and atolls. On this theory the thickness of the reefs is not greater than about 300 ft.—excepting where the living coral has grown on coral-rock talus. This theory is similar to Darwin's in that the coral upgrowth is conditioned by a rising shore level and accompanied by drowning of valleys of the coastal lands behind the barrier reefs. But the amount of relative subsidence postulated is restricted, and the foundations of the islands are considered to be stable.

Critics of the glacial control theory draw attention to the wide-spread evidence of independent vertical movements and tilting of the islands (i.e., want of stability) as given by the reefs now above sea-level, and to the evidence that some islands afford of submergences much greater than 300 ft. The rock bottoms in the embayments of many reef-encircled volcanic islands are believed to be of much greater depth and width than can be accounted for by the low-level erosion of still-standing islands during the glacial epochs. It is to be noted also that there is a considerable variation in lagoon depths. The lagoon in the large almost-atoll of the Exploring isles in eastern Fiji reaches a depth of 90 fathoms, whereas that of Christmas island, 15 miles across, is only 4 fathoms deep. However, most of such variations can easily be accounted for by varying conditions of deposition in the lagoons, and the absence of very deep lagoons remains a striking feature. An acceptable theory must account for the general rule; reasons can generally be found for exceptions.

A further consideration is of considerable importance. An island unprotected by reefs—the situation postulated in glacial times—must suffer erosion by the waves which cut into the land like a horizontal saw, producing at sea-level a rock platform which is bounded by steep cliffs. This condition is illustrated in Fig. 18, sector B. With rise of sea-level and renewed coral growth the valleys are inundated and the lagoon is formed behind the up-growing reef as shown in sector C. Cliff formation ceases, but one would expect plunging cliffs, being relics from those formed by the erosion of the reefless island, as in sector B. The reef-encircled islands of the main area of the coral seas are, however, prevailingly non-cliffed—a circum-

stance which falls in better with Darwin's theory, in which the island shores are considered to be those of a progressively drowned land which was continuously protected from marine erosion by an off-

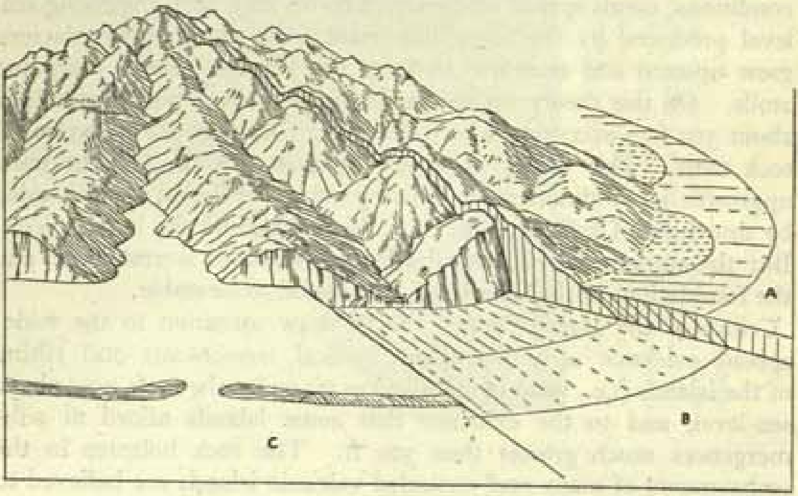

Fig. 18. Sector diagram showing the effects of a long period of low-level abrasion on a still-standing island

Sector A shows the island with fringing reef. B shows in its wave-cut platform and sea-cliffs the effects of marine erosion exposed as a result of a fall of sea-level. C shows the effects of a subsequent rise in sea-level with the formation of a barrier reef backed by a plunging cliff. Based on W. M. Davis, *The Coral Reef Problem*, p. 211 (New York, 1928).

shore living barrier reef. Cliffed islands are common, however, on the cold margins of the coral area (in the Hawaiian islands, for example) and over these relatively small areas the sequence of events postulated by the glacial control theory may have obtained.

The rarity of cliffed islands in the coral seas also bears pointedly on the suggestion that barrier reefs have not been built up on subsiding foundations, chiefly by corals, as Darwin proposed ; but have been built up on stationary foundations, chiefly by nullipores, which can live in deep and cold water, and that corals have only added a shallow crown to the great nullipore structures. If this were so, the originally conical islands, 'still-standing' and unprotected while the nullipores were building up their deep banks, would to-day have well-cliffed, non-embayed shores, whereas nearly all barrier-reef islands have well-embayed, non-cliffed shores.

It is clear that the histories of the reef islands have been various.

Fig. 19 illustrates the development of the Exploring isles and their small atolls, as imagined by W. M. Davis. The central portions of the sectors represent the larger islands, the outer ones the smaller islands. Sector A shows the initial forms due to volcanic eruption. Sector B shows the forms of well advanced erosion and partial submergence until only mountain-top islets survive with an almost-atoll reef, and atolls outside (sector C). Sector D represents the forms which would be shown by uplift without erosion, and sector E the forms actually realized when, elevation having ceased, the limestone area is for the most part stripped from the volcanic mounts and reduced to low relief. Sector F shows the forms of to-day, after the limestone area is submerged beneath the lagoon of a new barrier reef, above which rise the little modified volcanic mounts with their residual limestone patches.

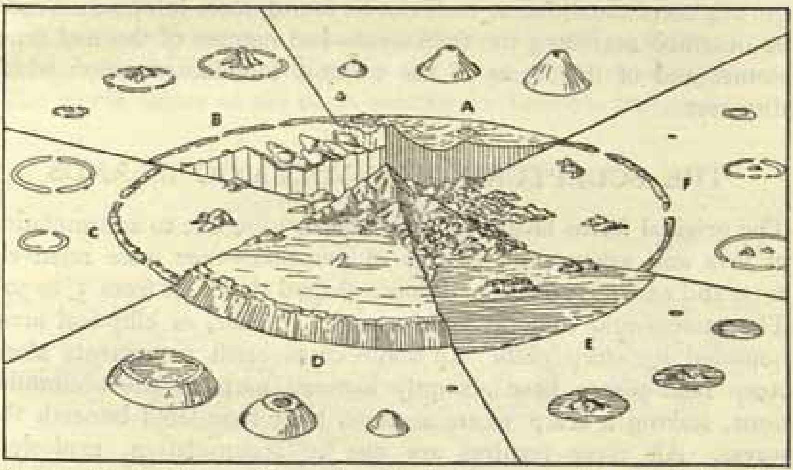

Fig. 19. Sector diagram illustrating the development of the Exploring isles, Fiji

Sectors A, B and C show the effects of various stages in subsidence. D shows subsequent elevation. E shows marine erosion of the platforms, and F the effect of later subsidence. Based on W. M. Davis, *The Coral Reef Problem*, p. 211 (New York, 1928).

Some of the reef-encircled islands have been deeply eroded—a process which takes a long time and involves the disappearance of great volumes of rock detritus. Such islands may have delta and coastal flats built of sediment delivered by rivers, but these deposits represent only a fraction (estimates of 1/50th and 1/100th have been made for some cases) of the material which has been removed. With

active delivery of sediment to coasts, coral growth is smothered, and the disposal of the detritus in such barrier reef islands presents a problem. It has been suggested that in the earlier stages of the erosion of these islands they were reefless, and that the sediment was distributed to off-shore waters by wave action; with subsidence the detritus was deposited in the drowned valley bays, whilst the barrier reefs grew upward on the banks of detritus off-shore.

After a period of scepticism and strong criticism, Darwin's theory has come into favour again, as affording the most valuable clue to the general solution of the reef problem, which is an extremely complex one.

The varied histories, ages, and situations of the reefs show that no one hypothesis can be adopted for all cases—each reef calls for individual study. Before convincing solutions to the problems of the origins of the different reefs can be found, more information must be obtained regarding the thicknesses and natures of the reef limestones, and of the forms of the volcanic foundations upon which they rest.

THE SCULPTURING OF VOLCANIC ISLANDS

The original forms of the volcanic islands were due to accumulation of lava and ash around centres of eruption—they were relatively even and smooth, conical and dome-shaped slopes, at from 5° to 30°. The craters and calderas were central, circular, or elliptical areas bounded by steep cliffs. In some cases earth movements along steep fault-planes have abruptly lowered parts of the accumulations, leaving a scarp where sections have foundered beneath the waves. All these features are due to accumulation, explosion,

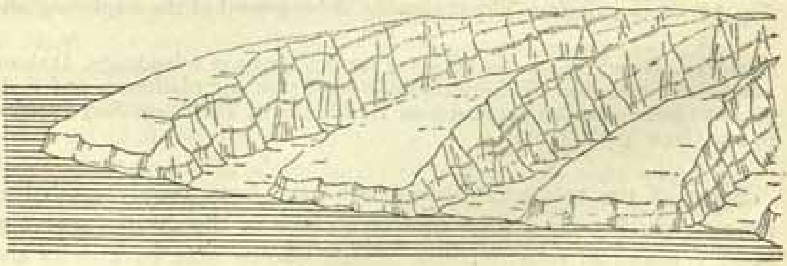

Fig. 20. Sub-mature dissection of a volcanic island
The island was initially a basalt dome. Based on C. A. Cotton, *Geomorphology*, p. 372 (3rd edition, Christchurch, 1943).

and earth movements. With the cessation of volcanic activity, the slow action of the forces of erosion proceeds to modify the original land forms (Plates 26–7). In time all traces of the original surfaces are lost, and the final stages—given a long enough 'still-stand' of shore level—are those of a low island and, eventually, a submarine bank.

The process starts with the development of streams in the lower regions of the volcanic pile, and these form valleys radiating outward from the centre like the spokes of a wheel. With the continued widening of the valleys, ridges are left between them in the upper parts where the valleys are closer together, whilst the original slopes may still be preserved at lower levels (Fig. 20). Eventually, all the original slopes disappear, and the radial valleys and the outward dips of the lavas and ash beds revealed in the valley sides remain as witness of the site of the now degraded volcano.

Caldera walls become reduced in time and a valley cutting backwards into the dome may reach and drain the central depression. The whole centre of the main volcano in Tahiti is replaced by the

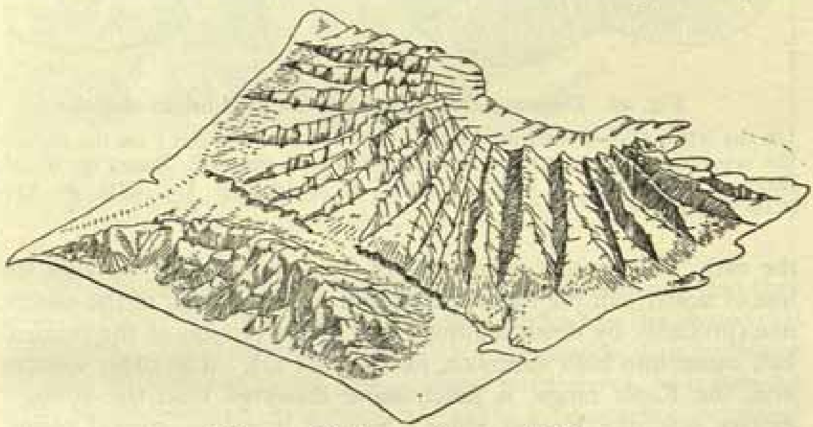

Fig. 21. Bird's-eye diagram of Oahu

The diagram shows contrasts in the dissection of the leeward and windward sides of the island. Based on W. M. Davis, *The Coral Reef Problem*, p. 170 (New York, 1928).

Papenoo valley, which is surrounded by a ring of high residual peaks. It is difficult in such a case to determine, after such prolonged erosion, whether the central area is primarily the site of an original caldera, or whether its surface has been largely lowered as a consequence of headward valley erosion. Great hollows presumed

to have been eroded in the centres of volcanic mountains are termed 'erosion calderas' in contradistinction to the original volcanic crater caldera.

The stages of erosion may vary greatly on the sides of a dome if there is a difference in rainfall, as in Hawaii. The rainy windward side may reach an advanced stage of dissection and acquire a very rugged appearance, whilst the leeward side retains much of its smooth dome-like form (Fig. 21). Apart from this consideration it may be said that the more dissected an island is, the longer the period which has elapsed since the cessation of volcanic activity.

The development of land forms in volcanic islands may be illustrated from the island of Oahu (Hawaii). The original island was a volcanic doublet (Fig. 22), the younger and larger cone lying to

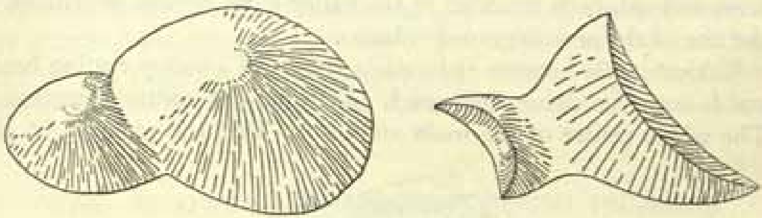

Fig. 22. Diagram illustrating the structural origin of Oahu

On the left is shown the initial form of the volcanic doublet; on the right is the residual doublet after the loss of part of each volcano. Based on W. M. Davis, 'The island of Oahu', *Journal of Geography*, vol. XXII, p. 354. (Chicago, 1923).

the east. The present island differs from the original through the loss of nearly half the western cone and more than half of the eastern one (probably by down-faulting), and by the erosion of the residual half cones into bold mountain forms (Fig. 21). The older western one, the Kaala range, is much more dissected than the younger eastern one, the Koolau range. Several limestone coastal plains, now partly overwashed by volcanic detritus from the mountains, occupy the wide valleys of the western coast; a smaller one lies in the northern re-entrant angle between the two cones; and the largest stretches all along the southern coast. The largest varies in width from several hundred feet to two to three miles, and along its landward boundary lie limestone cliffs denoting a former shore line. Also there is a coastal plain almost wholly composed of volcanic detritus at the base of the great cliff, the Pali, in which the broken-down younger cone faces the mid-eastern coast. The cliffs of the

younger cone, being on the windward side of the island, receive a heavy rainfall and are clothed with verdure, while the deeply eroded seaward slopes of the older cone on the leeward side of the island are relatively dry and have scanty vegetation.†

Cliffs are formed where marine erosion, in the absence of a coral reef, is active (Fig. 23). Their presence at the shores of a lagoon

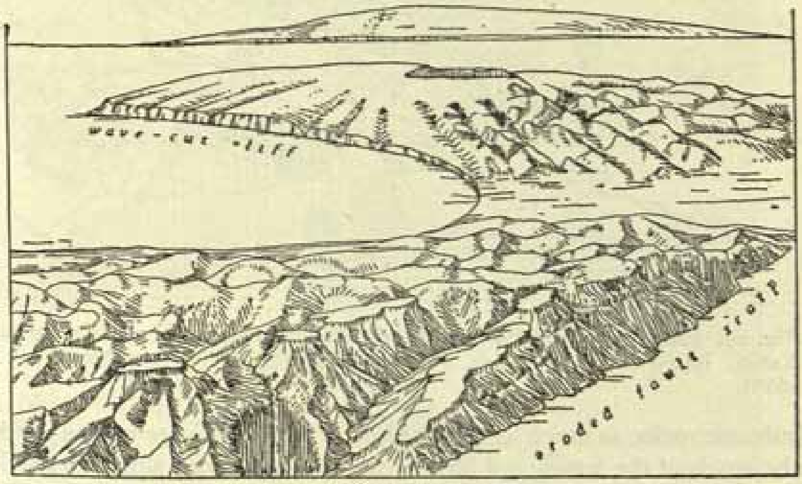

Fig. 23. Maturely dissected lava domes

The diagram shows cliffs formed when bounding reefs are absent. Based on A. K. Lobeck, *Geomorphology*, p. 676 (New York, 1939).

behind a barrier reef may be explained on the hypothesis that they were formed before the reef was in being, and when the shore level was lower. Flat lowland at the borders of islands may represent uplifted sea floor, as in the case of Oahu cited above, or it may be built of land-derived sediment. In Tahiti submergence produced drowned-valley embayments (Fig. 24), all of which are now filled with delta plains, save for some small unfilled bays where the streams in the valleys at their heads are short and small. These level plains have advanced far enough outside the former bays to become laterally confluent in a narrow alluvial lowland (built up from volcanic detritus and up to 1,000 ft. broad) around much of the coast of Tahiti. Behind these coastal plains with their rich soil are cliffs cut out of

† For another interpretation of the geological history of Oahu, see H. T. Stearns and K. N. Vaksvik, 'Geology and Ground-water Resources of the Island of Oahu', *Division of Hydrography, Bulletin*, I (Honolulu, 1935).

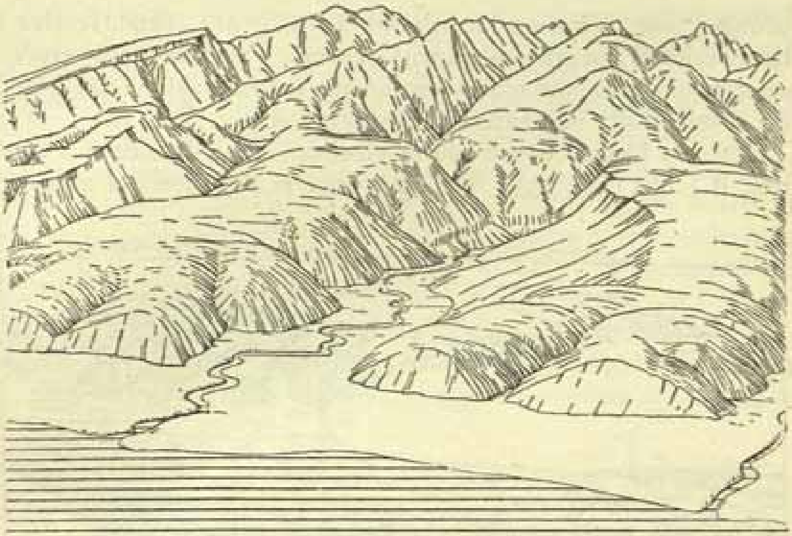

Fig. 24. Embayed and delta-filled valley between two spurs, north coast of Tahiti. Based on W. M. Davis, *The Coral Reef Problem*, p. 255 (New York, 1928).

volcanic rocks, as much as 500 ft. high. These cliffs are now beyond the reach of the waves and have weathered into steep slopes masked by clay and rubble.

DEPOSITS ON THE FLOOR OF THE PACIFIC

In shallow water adjoining the land, material accumulating on the sea floor is sand and mud derived from the land masses—the so-called terrigenous deposits. The material becomes finer in particle size with increasing distance from the shore. Water charged with sediment in suspension is heavier than clear water, and it slides down the continental slopes beneath the stiller upper waters for tens of miles before all its load is dropped ; thus the muds often extend 200 miles from the shore.

The main area of the Pacific is out of reach of this material, and the deposits are of two main types—the ooze and the red clay. The oozes are composed of the skeletons of tiny organisms (plankton) which live mostly near to the surface and which on death slowly rain down towards the ocean floor. In the globigerina and pteropod oozes the skeletons are of calcium carbonate; in the diatoms and radiolaria they are of silica. The distribution of the various oozes (Fig. 25) is obviously governed by the nature of the dominant

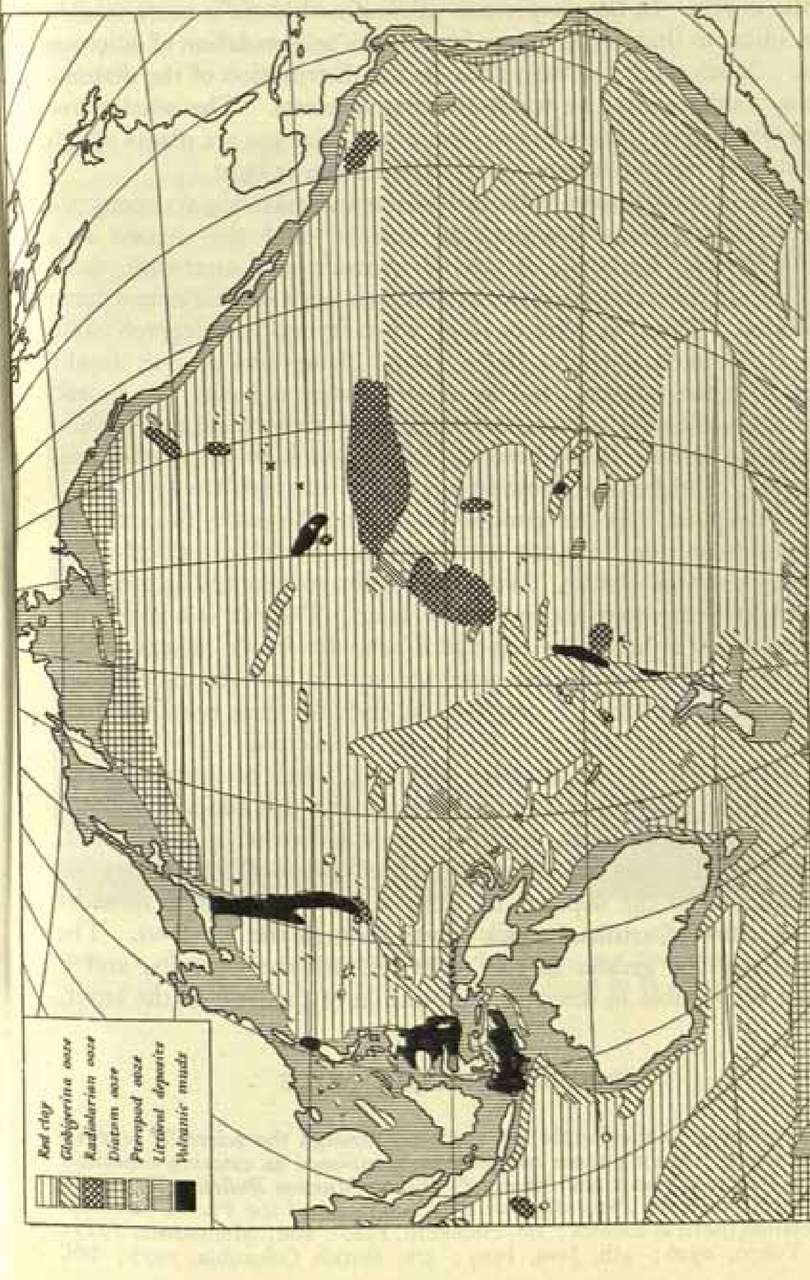

Fig. 25. Distribution of submarine deposits in the Pacific basin
Based on G. Schott, *Geographie des indischen und stillen Ozeans*, Tafel V (Hamburg, 1935).

planktonic life in the waters above them; but it is also controlled by the depth. In the deep water calcium carbonate is more soluble than silica, so that deeper water favours the accumulation of siliceous ooze. Much work has been done on the distribution of the diatoms in the southern seas by whale-hunting interests. The whales live on prawns which in turn live on diatoms. Diatoms are plants which live only in the uppermost 150 ft. where there is light.

In the deepest waters both calcareous and siliceous skeletons are absent—having been dissolved on descent—and the deposit is a fine 'red clay' made up of altered volcanic and meteoritic dust, with no organic remains save the resistant teeth of sharks and bone of whales. Thus the *Nero* in 1899, when laying the telegraph cable from the United States to Japan, found globigerina ooze at depths down to 2,200 fathoms, and in deeper water, red clay was found. This deposit contains manganese, giving it a chocolate colour, and manganese nodules have been dredged from it in great numbers. Spherules of nickel-iron (cosmic meteoritic material) are also found.

The deep-sea deposits grow slowly. For the oozes the estimate is from about 1 in. in 2,000 to 6,000 years, whilst the rate for the red clay must be slower. With the Piggot core-sampling gun it is possible to bring up cores up to 10 ft. long. The gun is a long brass tube with a weight on the top and a cartridge inside (Plates 28–9). On reaching the bottom the cartridge is fired and the tube driven far into the deposits. A core of red clay has thus been obtained 220 miles west-south-west of San Diego, California.

If the Pacific ocean has existed since the birth of the earth (say, 2,000 million years ago) it has been estimated that the accumulated and compacted deep-sea sediments may be about 4 miles thick. There is good hope that in the future it will be possible to determine the thickness of the deposits by using seismic methods to measure the velocities of artificial shock waves through the sea floor. The velocity will be greater in the rocks beneath the deposits, and it should be possible to discover the position of the base of the latter.

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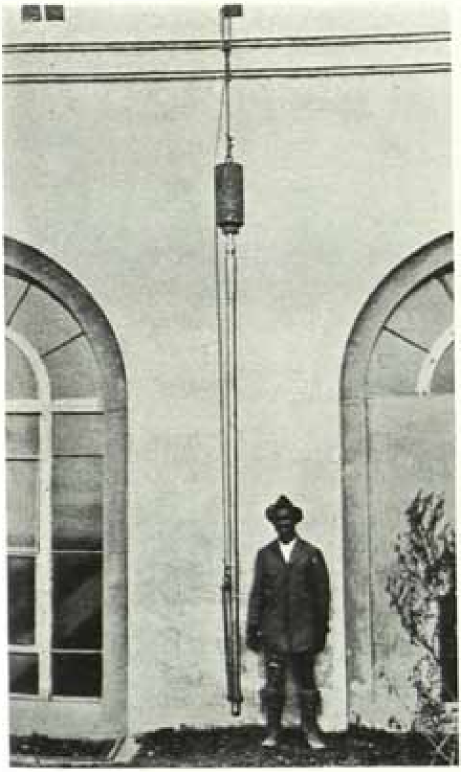 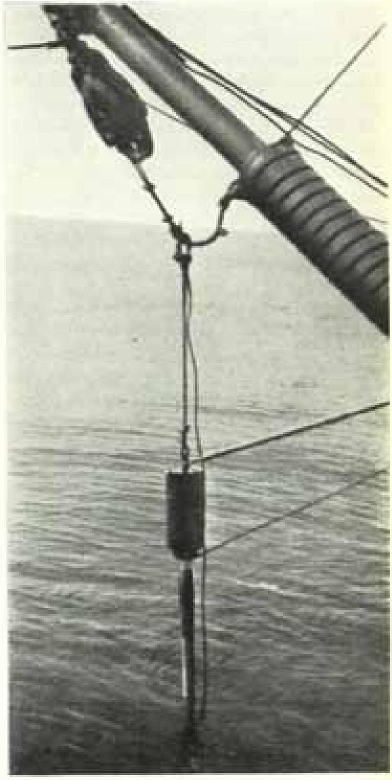

Plates 28–9. Piggott core-sounding apparatus

Plate 28 shows the apparatus assembled ready for lowering. Plate 29 shows it suspended on the ship's sounding cable and about to be lowered; the safety pin is being pulled by means of a lanyard.

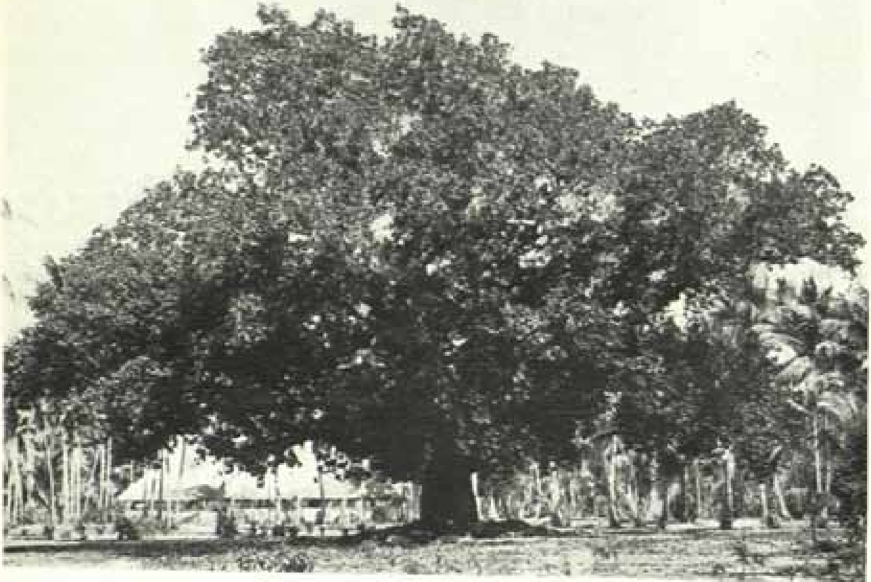

Plate 30. *Calophyllum inophyllum*
A common tree of the sea coast throughout the Pacific islands. It is also known as native almond or *tamanu*.

Plate 31. Beach vegetation, Nauru
In the foreground are low-growing herbaceous plants ; in the background coconut palms and pandanus trees.

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Chapter III

CLIMATE

Pressure and Wind: Temperature: Humidity: Visibility and Fog: Rainfall: Bibliographical Note: Climatic Tables

Since the Pacific ocean is divided by the equator, the climatic elements are reproduced more or less symmetrically in either hemisphere. The axis of symmetry in any particular month is the equatorial belt of low pressure or 'doldrums', the position of which is described below. It is a region of light variable winds, preponderantly easterly in direction, towards which blow the trade winds, diminishing in force and reliability as they approach the trough of lowest pressure where the constantly incoming air escapes upwards. The doldrum

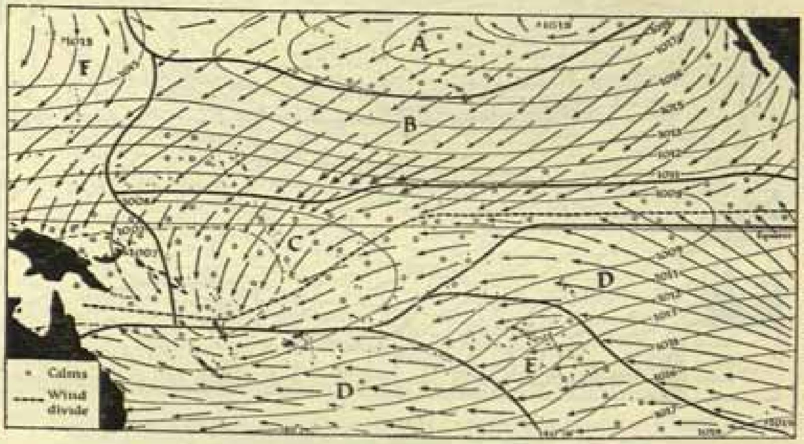

Fig. 26. Pressure, winds and wind belts: January–February

The letters refer to the following regions: A, variables of the tropic of Cancer; B, the north-east trades; C, the doldrums; D, the south-east trades; E, the variables of the tropic of Capricorn; F, the monsoons. The figures show pressure in millibars. Based on G. Schott, 'Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, p. 90 (Berlin, 1938).

belt migrates north in the northern summer to a limiting position about 5° N in July and August, whence it retreats to the other extreme in January and February. At this season it is in general still north

of the equator to the east of long. 160° W (Christmas island), but bulges as far as 10° or 12° S near the Ellice islands and the Solomon islands.

The source regions of the trade winds are the high-pressure belts lying about 30° N and S. As a result of a procession of anticyclones moving eastwards, the mean pressure is generally high right across the ocean in these latitudes. It is highest towards the eastern side of the ocean in each hemisphere where the mean isobaric map shows oval highs in the centre of which pressure exceeds 1020 mb. The mean position of these high pressure areas changes very little with the seasons; the details can be seen from Figs. 26 and 27.

The trade winds blow with great regularity from east-north-east on the north side of the doldrums, and from east-south-east on the

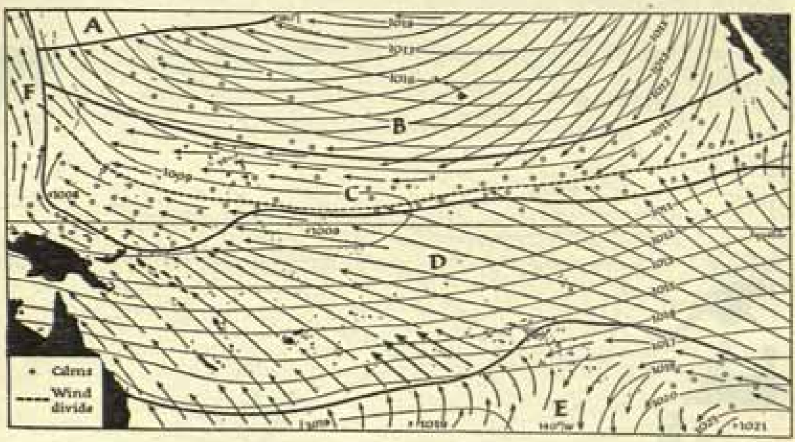

Fig. 27. Pressure, winds and wind belts: July–August

The figures show pressure in millibars. Key to regions and source as for Fig. 26.

south side. They prevail over the whole of the width of the ocean except for a narrow belt on the east and a much wider belt on the west.

On the east side near the American coast, the winds, circulating round the anticyclones described above, blow parallel with the coast, from the south off South America and from the north off California. The south winds extend across the equator and prevail

at Cocos island from April to October and at the Galápagos from March to January (the *garúa* season—vol. II, p. 25).

Such, in broad outline, is the scheme of winds in the mid-Pacific and in the Eastern Pacific between 30° N and 30° S. It is simple and symmetrical, but west of about 150° E the symmetry of winds and other climatic elements is destroyed by the influence of the great land mass of Asia with its powerful monsoon, which strongly affects the climate to a distance of over 1,000 miles from the mainland. Because the north Pacific is bordered by the two largest land masses

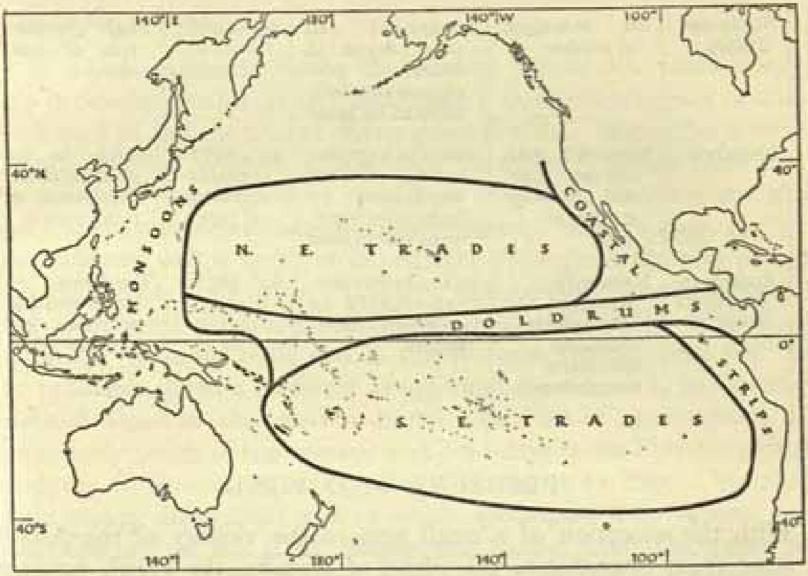

Fig. 28. Climatic regions of the inter-tropical Pacific

The regions are defined according to their prevailing winds. The winds of the 'coastal strips' blow parallel with the American coasts. Based on various sources.

of the world its seasonal contrasts are more pronounced than those of the wide south Pacific, with its relatively small and discontinuous flanking land masses.

The inter-tropical Pacific can thus be divided into regions of prevailing winds (Fig. 28). Since the nature and source of the air currents is the chief factor in determining other weather phenomena, these wind regions become climatic regions, the chief characters of which may be tabulated, in very general terms, as follows :

Region	Prevailing Wind	Rainfall	Temperature	Remarks
North-east trades	ENE; strongest in winter	50–100 in.; all year. Heaviest precipitation on windward side of high land	66°–78° F.	High proportion of sunshine
Doldrums	Easterly; light and variable	100–150 in.; all year, autumn maximum	78°–82° F.	Muggy; night thunderstorms in rainy season
South-east trades	ESE; strongest in winter	50–150 in.; all year, driest in winter; precipitation greatly affected by relief	60°–80° F.	High proportion of sunshine
Monsoon	Reversed with seasons: light and variable at change-over	100–150 in.; seasonal, summer maximum; highest on windward side of land	62°–84° F. considerable range off Japan	Liable to typhoons, thunderstorms in rainy season
American coastal strip	Northerly (northern hemisphere); southerly (southern hemisphere)	60 in.; rather dry, especially in southern hemisphere	60°–78° F.	Tendency to cloud and fog in shore, especially outside the tropics.

PRESSURE AND WIND

With the exception of a small area in the vicinity of the Asiatic coast from Shanghai to the island of Kyushu, the Pacific between 30° N and 30° S is seldom affected by temperate depressions, and within this belt the pressure is remarkably uniform. The highest pressure is 1026 mb. (near Hawaii) and the lowest 1006 mb. (near New Guinea). The yearly range at any one place, due to the seasonal migration of the pressure systems, nowhere exceeds 10 mb. and the day-to-day variation is so slight as to be negligible. Under these conditions, the diurnal variation of pressure is clearly recognizable and is remarkably regular and reliable. It reaches maxima at 1000 hr. and 2200 hr. and minima at 0400 hr. and 1600 hr., the amplitude being about 3 mb. This regular rise and fall twice daily is only interrupted by the rare introduction of a deep low pressure (tropical cyclone) whose approach may be detected in single observer forecasting by the failure of the daily maximum to attain that of the

previous maximum. Any noteworthy disturbance of the settled course of the barometer changes should therefore be regarded seriously, as a possible precursor of development of a typhoon. During a typhoon the barometer descends very low, perhaps 50 mb. (fifteen times the normal diurnal variation).

The broad features of pressure and wind systems have already been described. Details of the direction and reliability of the winds for January, April, July and October are given in Figs. 29–32; they are described below.

The Doldrum Belt

It will be noticed that in the Eastern Pacific the trade winds are decidedly north-east and south-east; their convergence is thus well marked and the area of convergence is wide. But in the central Pacific and the Western Pacific their direction is almost from east to west, the two air streams are almost parallel in direction and the zone of convergence is narrow and ill-defined. East of long. 165° W, the doldrum belt is north of the equator throughout the year and is situated in lat. 5° to 10° N. It is well defined from June to January, but the typical conditions occur only irregularly in the other four months. In mid-Pacific and in the Western Pacific, from 165° W to 155° E, it shows a tendency to split and spread; it is less clearly defined than in the eastern part. The line of convergence is commonly south of the equator and lies between the Phoenix group and the Solomons, especially from December to May. Variable light winds, often from west or south, accompanied by storms, are characteristic of the Cook islands and Samoa from December to March. From June to October, however, the line of convergence is usually to the north of the equator in the neighbourhood of the Caroline islands and Guam. Though the wind is typically light and flat calms are frequent, the doldrums are liable to violent squalls, usually of short duration, accompanied by thunder, lightning, heavy rain, and, not infrequently, waterspouts. The storms mostly occur at night. There is much heavy cloud and rain.

Trade Winds

It can be seen from Figs. 29–32 that the trades of the northern hemisphere are more constant in direction than those of the southern. In the middle and eastern parts of the north Pacific 60% to 90% of winds follow the prevailing direction; in the southern Pacific

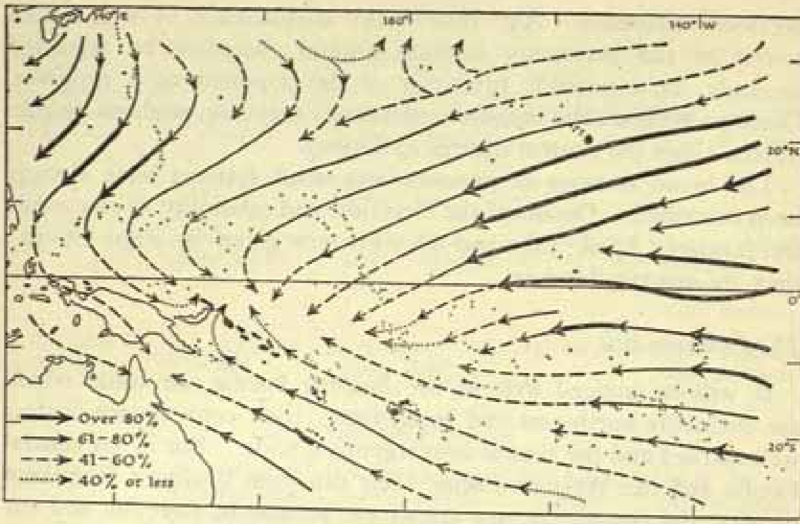

Fig. 29. Average surface wind-drift: January

Figs. 29–32 show the percentages of winds which follow the prevailing direction. They are based on the U.S. Hydrographic Office, 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), pp. 11–15.

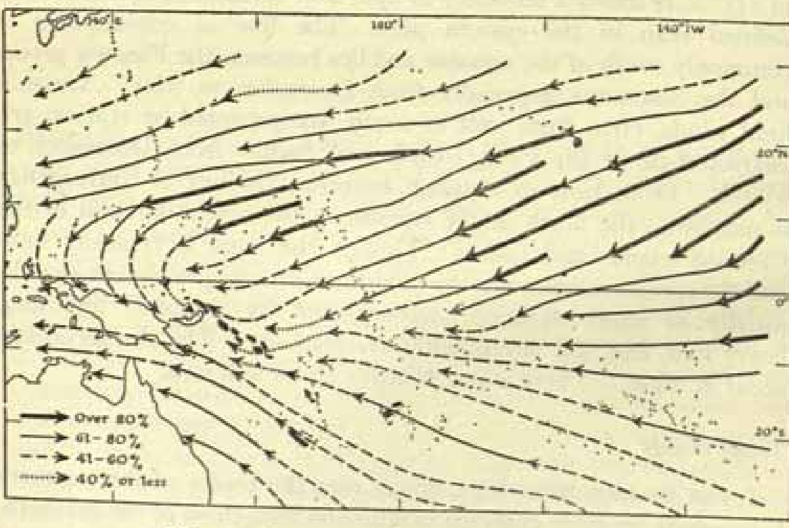

Fig. 30. Average surface wind-drift: April

For explanation and source see Fig. 29.

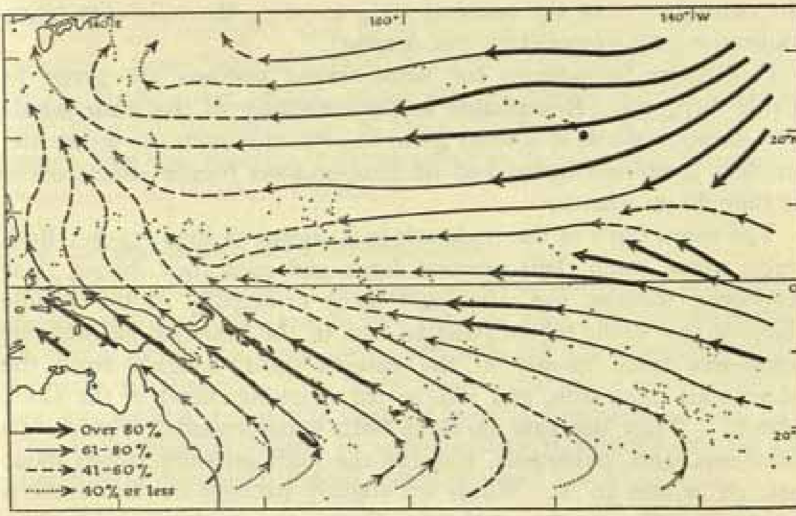

Fig. 31. Average surface wind-drift: July

For explanation and source see Fig. 29.

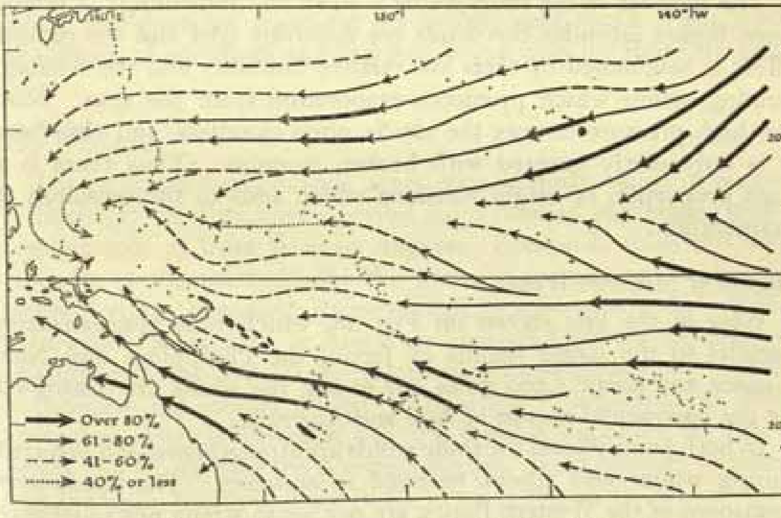

Fig. 32. Average surface wind-drift: October

For explanation and source see Fig. 29.

the constancy is of the order of 50% to 70%, the reliability being highest in mid-winter (July and August).

Percentage frequencies for some island stations are given in Table I (p. 90). Remarkable as the constancy of the trade winds is at these stations, it is even more so over the open sea where the air flow is uninterrupted and no land-and-sea breeze effects occur as they do on islands.

The mean force of the trade winds is shown in Figs. 33–6. Both trade winds reach their greatest force and constancy during their respective winters, the north-east trade principally in the middle third of the whole region (that is, east of the Marshall islands) the south-east trade mostly in the eastern third, roughly from the Marquesas eastwards, and also in the neighbourhood of the Cook islands. They decrease in force both equatorwards, towards the doldrums, and, polewards, towards the high pressure ridges about lats. 30° N and 30° S. Winds are slightly stronger in the northern hemisphere than in the southern. Owing to retardation by friction the winds recorded at island stations are about 3 knots less than over the open sea.

Table II (p. 95) shows that from half to two-thirds of winds are between 4 and 14 knots and that winds exceeding 28 knots (force 7 and over on the Beaufort scale) are rare.

The weather of the trade winds is brisk and refreshing. Coming from higher latitudes the winds are relatively cool and the cooling effect is heightened by their low relative humidity and the constant fanning action which promotes evaporation from the skin. Near the high-pressure centres the sky is often cloudless, and elsewhere it is only partly covered with broken cumulus. Thus there is a high proportion of bright sunshine which adds to the sensation of invigoration.

Region of Monsoon Winds

West of the line shown on Fig. 28, which runs approximately parallel to the larger islands of Japan, the Philippines and New Guinea and about 1,000 miles out to sea, the winds are controlled by the continental masses of Asia and Australia.

In both hemispheres the trade winds are strengthened and diverted during winter and almost reversed in summer. The south-west monsoons of the Western Pacific are neither so strong nor so reliable as those of the Indian ocean, but the north-east monsoons are stronger than those of the Indian ocean.

Winds are strongest and most reliable at the height of each monsoon, from July to August and from December to February. At the change-over season, calms and variable winds are frequent and the region becomes part of the doldrums. It is partly for this reason that the doldrum belt of calms is so wide and variable in position in the Western Pacific.

The 'Horse Latitude' High Pressure Belts

The frequent passage of anticyclones across the ocean in latitudes about 30° N and 30° S results in a ridge of high mean pressure that, in effect, forms the wind divide between the trade winds and the westerly circulation. The trade winds weaken as these latitudes are approached and winds become light and variable in direction. The high pressure results in a descending motion of the air and therefore in dryness of the air and absence of cloud.

The American Coastal Strip

Off these coasts the prevailing winds are directed towards the doldrums that lie roughly on the equator in February and off Mexico in August. A cold current flows from the south up the coast of Peru and swings westwards where the coast changes direction off cape Blanco in Ecuador. A similar current off California has less power and does not make the sea unduly cold south of the tropic of Cancer. Low cloud and fog may occur with on shore winds off Peru.

The Westerlies

The most southerly islands experience westerly winds in winter; at Rapa (27° S) west winds prevail from May to September and at Norfolk (29° S) from June to August. Polewards from the horse latitudes in the north Pacific the prevailing winds are westerly or south-westerly, becoming stronger with increasing latitude. Where these winds meet polar or Arctic air blowing from the cold regions of north-east Asia and Alaska cyclonic storms are generated. Winter is therefore the stormy season. The average frequency of these storms in winter is shown in Fig. 37; it is highest along the line of Japan, the Kurile and the Aleutian islands, which appears to represent the mean position of the Polar Front in the north Pacific. Only the western end of this storm belt, off Japan, concerns the present Handbook, but it causes a rapid increase in frequency of gales to the north of 30° N (Table III (p. 96)—Tatoosh island figures).

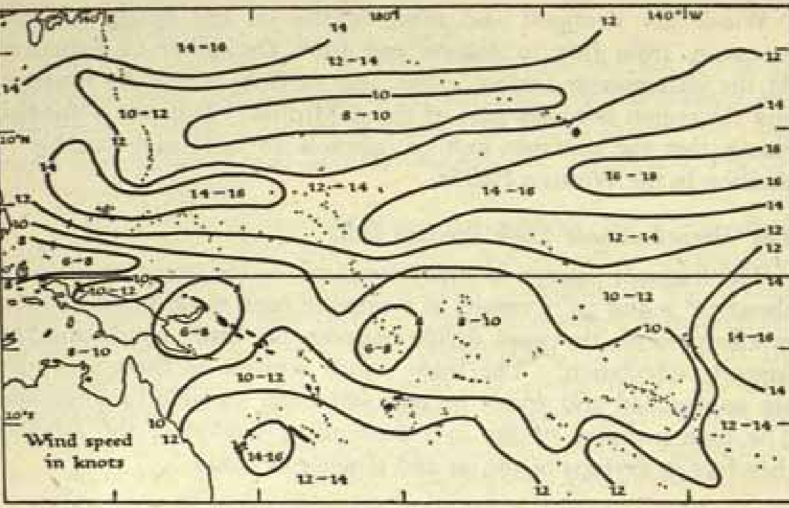

Fig. 33. Average surface wind speed in knots: December to February

The values shown in Figs. 33–6 are computed by conversion from the average Beaufort numbers in ships' observations. Figs. 33–6 are based on the U.S. Hydrographic Office, 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184, pp. 19–20.

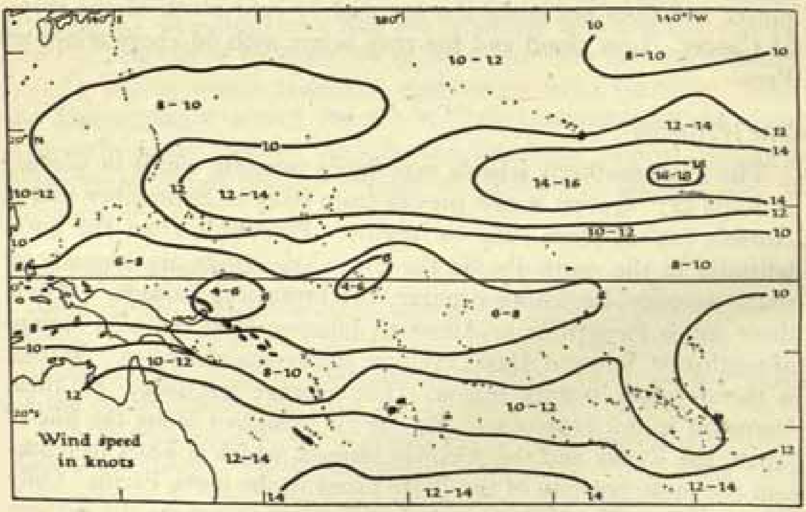

Fig. 34. Average surface wind speed in knots: March to May

For explanation and source see Fig. 33.

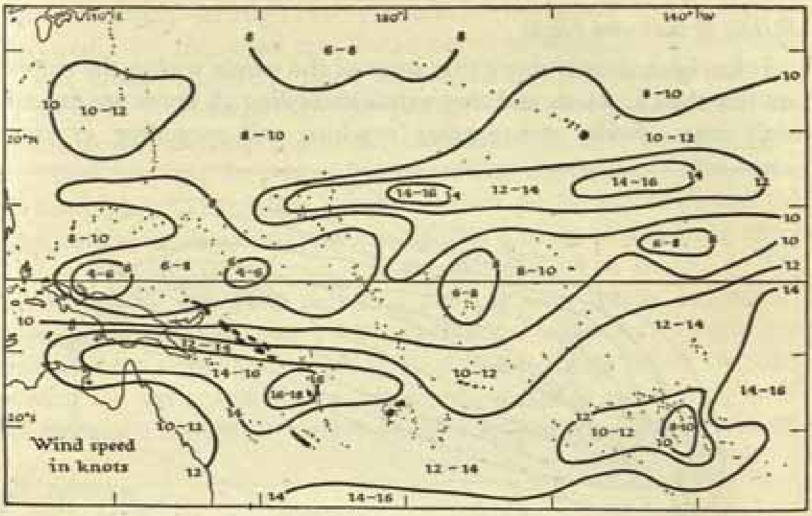

Fig. 35. Average surface wind speed in knots : June to August
For explanation and source see Fig. 33.

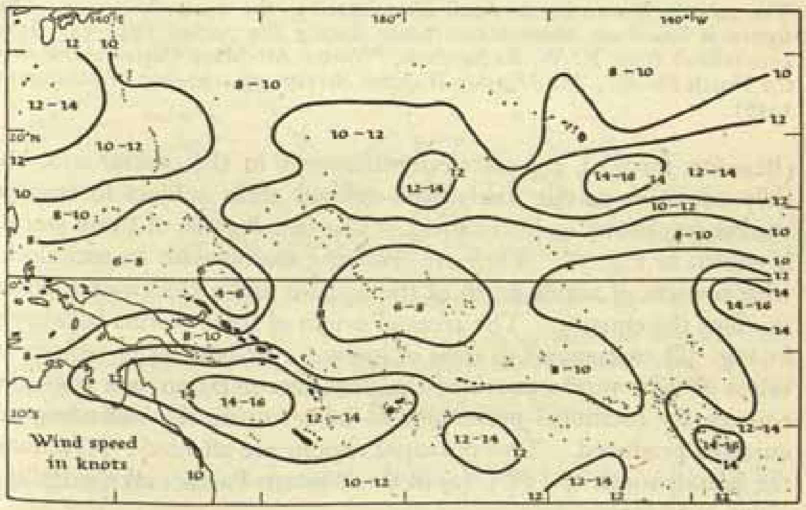

Fig. 36. Average surface wind speed in knots : September to November
For explanation and source see Fig. 33.

Strong Winds and Gales

It has been shown above that most of the winds within the tropics are less than 14 knots and that winds exceeding 28 knots are exceedingly rare. Really strong gales, reaching and exceeding 41 knots

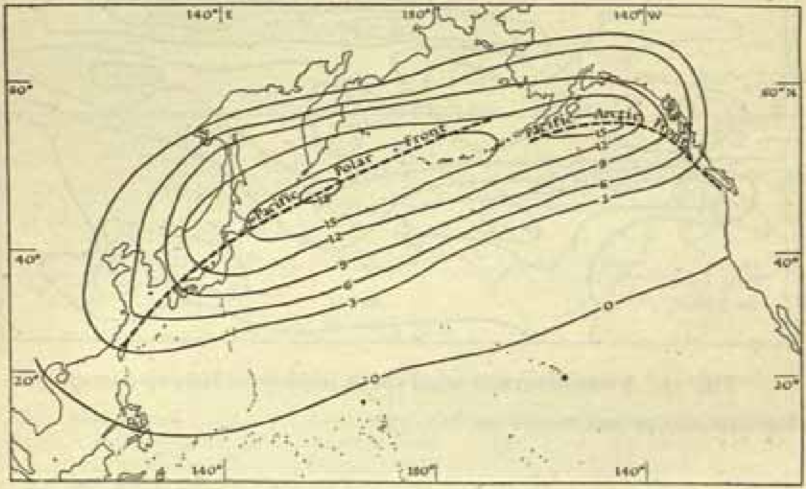

Fig. 37. Average frequency of depressions in winter

The months November to April are selected as the winter half-year. This figure is based on observations made during the period 1923–32. It is generalized from R. W. Richardson, 'Winter Air-Mass Convergence over the North Pacific', *The Monthly Weather Review*, pp. 199–203 (Washington, 1936).

(Beaufort force 9), are practically unknown in the central area, but they occur in certain fairly well-defined areas subject to tropical storms (typhoons or hurricanes). The distribution of these storms is shown in Fig. 38. They are revolving storms with an anti-clockwise rotation of winds north of the equator and a clockwise rotation south of the equator. The areas of origin of these storms (as shown in Fig. 38) correspond to areas of intense over-heating in regions of calms or light winds, provided that these occur far enough from the equator for rotational movement to be set up in the ascending air currents produced. Two principal regions are affected: (1) among the islands south of 15°s; (2) in the Western Pacific, off the Philippines and Japan.

In the northern hemispheres these storms generally follow a well-defined pattern of track—first westwards, then northwards,

then eastwards—though (exceptionally) many other routes may be followed. In the southern hemisphere, however, a curved track is not often followed; most storms move from north to south (Fig. 38). Not every typhoon produces winds of gale force, but probably half of them do, while velocities of 70 or 80 knots may be expected and 134 knots has been recorded on Guam. The radius of the typhoon circulation seldom exceeds 300 or 400 miles and the area of destructive winds may extend over a circle of about 100 miles radius from the centre, but it is usually less. The centre, or 'eye of the storm', though a region of calm or light winds, has mountainous sea and swell of a very destructive character. Torrential rain characterizes the central area, often producing 20 in. or more during the day or two of its passage; the record is 46 in. in 24 hours at Baguio, a mountain station in the Philippines. The hurricanes

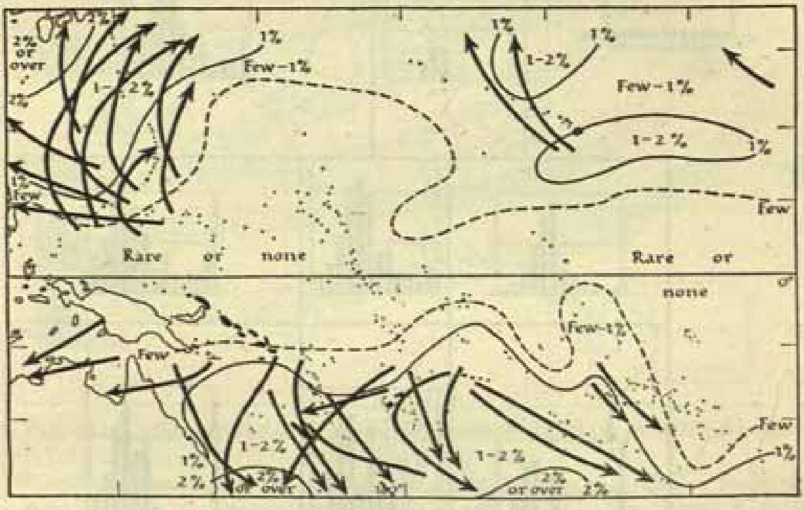

Fig. 38. Annual percentage frequency of strong gales and hurricanes

This figure records the frequency of winds of 41 knots or over (Beaufort force 9 or higher). The arrows show typical tracks of typhoons. Based on the U.S. Hydrographic Office, 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), chart 24.

of the south Pacific are not so violent as the typhoons of the China seas, but do great and lasting damage to low islands and atolls. These are sometimes completely washed over by the mountainous seas, with the destruction of every building and all crops.

In the south Pacific, hurricanes originate about lat. 10° s in the western half of the ocean and sweep south to about 30° s, but increase in frequency towards the west, affecting especially Samoa, Tonga, Fiji, the New Hebrides, New Caledonia and the coast of Queensland. Gales in these parts are mostly due to this source and about three per year may be expected (Table III, p. 96), mainly in the months of January to March.

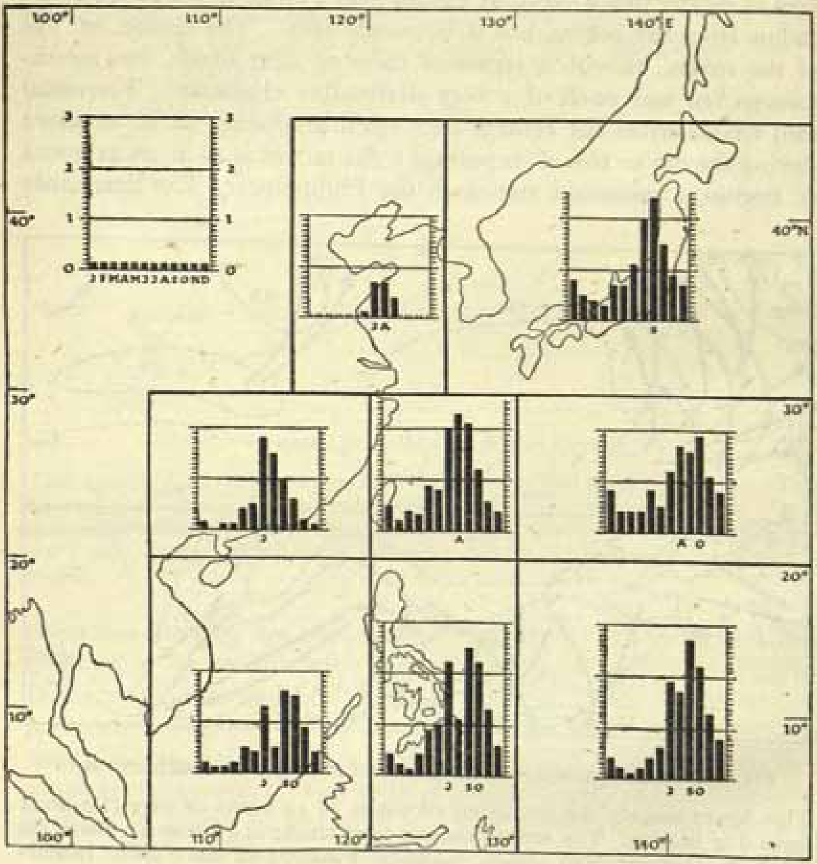

Fig. 39. Typhoon frequency in the China seas

The figure is calculated from observations over the periods 1893–1918 and 1929–31. The scale of frequency is indicated in the top left-hand corner of the map. The numbers show the averages per month. Months with maxima of typhoons are indicated by initial letters. Based on the Air Ministry Meteorological Office *Weather in the China Seas and in the Western Part of the North Pacific Ocean*, vol. 1, pt. 2, pl. 16, fig. 28 (London, 1938).

In the north Pacific hurricanes occasionally occur in the neighbourhood of the Hawaiian islands, originating about 15° N; but they are unusual features of the climate there.

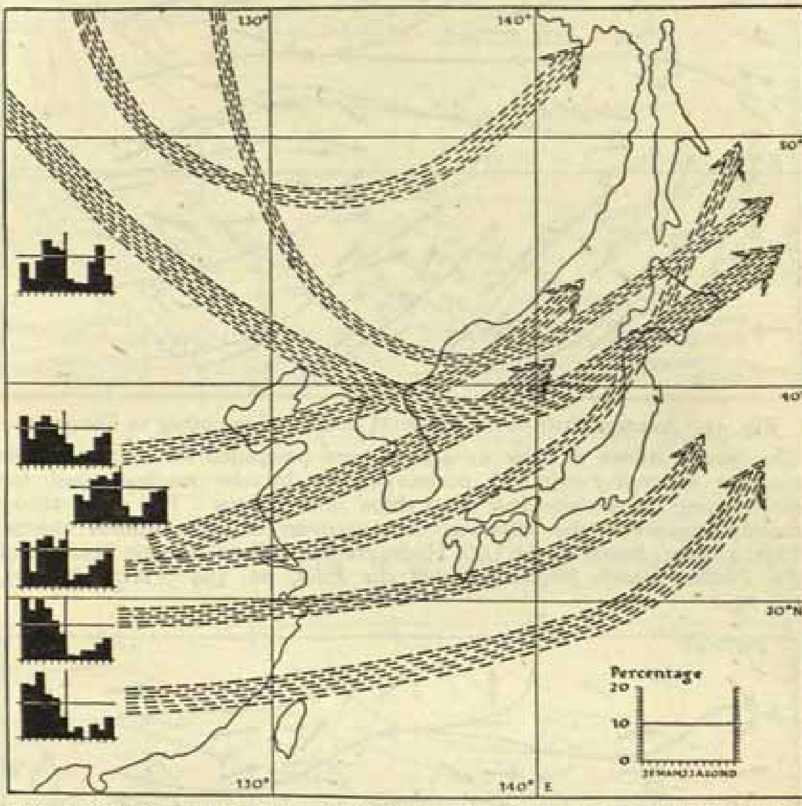

Fig. 40. Typical tracks of cyclonic depressions and their monthly frequency over the China seas

The thickness of the band indicates approximately the relative frequency with which depressions travel along these tracks. The diagram at the beginning of each track indicates the percentage frequency of depressions on that track in each of the twelve months; a vertical line has been drawn between the columns for June and July. Based on the Air Ministry Meteorological Office *Weather in the China Seas and in the Western Part of the North Pacific Ocean*, vol. 1, pt. 1, p. 53 (London, 1938).

In the China seas typhoons are an important element in the climate. They originate between latitudes 7° and 16° N according to the season, as follows:

	J	F	M	A	M	J	J	A	S	O	N	D
Lat. of origin (° N)	8	7	7	9	13	15	15	16	15	12	10	9

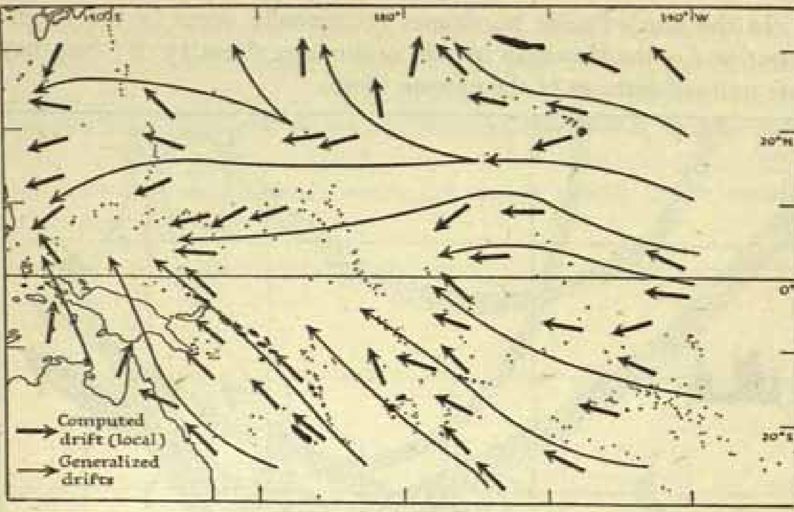

Fig. 41. Average drift of middle-level clouds: December to February

The results shown in Figs. 41–4 have been computed for a considerable number of well-distributed ocean squares by the method used for generalizing the surface drift from ships' observations. The observations mainly concerned the direction of movement of alto-cumulus clouds. Figs. 41–4 are based on the U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), pp. 25-6.

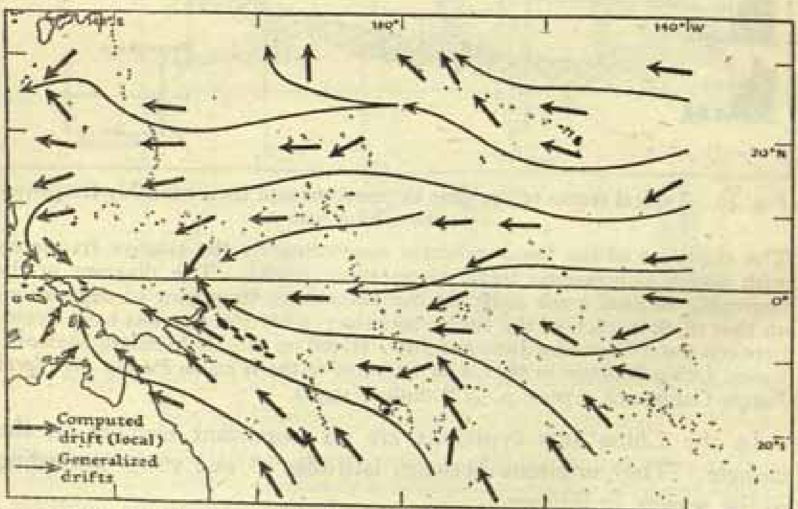

Fig. 42. Average drift of middle-level clouds: March to May
For explanation and source see Fig. 41.

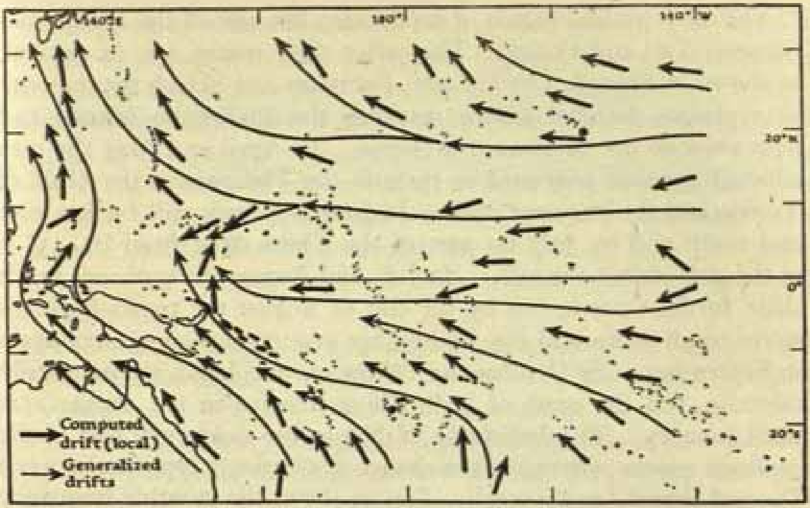

Fig. 43. Average drift of middle-level clouds : June to August
For explanation and source see Fig. 41.

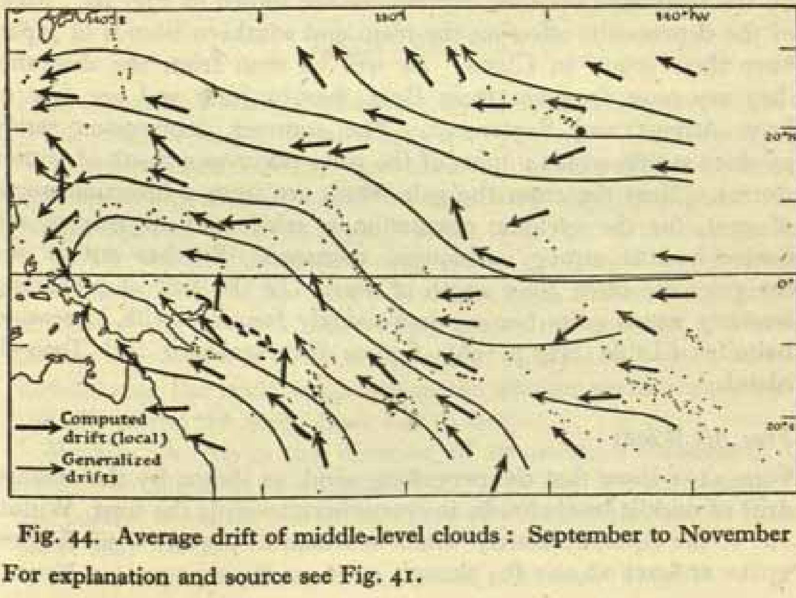

Fig. 44. Average drift of middle-level clouds : September to November
For explanation and source see Fig. 41.

The most prolific region of production lies east of the Philippines between Yap and Guam. Thereafter their tracks are, in general, as shown in Fig. 38. In January, February and March the majority of typhoons recurve before reaching the Philippine islands and pass away to the southward of Japan. In April and May the area affected spreads westward to include the Philippines, the Gulf of Tonkin and the Formosa strait. In June it spreads still further west and north and by July no part of the China coast from lat. 15° N to the gulf of Pohai is safe. In July and August the typhoons reach their furthest north, but by the end of August the tracks begin to move south again and the Philippines are in the danger area again in September. By October the Yellow sea and Japan are practically immune, but the coast of Indo-China remains in the danger area until January. The beginning of November marks the end of the typhoon season proper and the chance of meeting a typhoon between December and April is small. Fig. 39 shows the monthly frequency for eight rectangles of latitude and longitude.

Some of the gales occurring off China and Japan, especially during the winter months, are due to depressions of temperature origin and not to tropical revolving storms. Gales of this origin increase in frequency further north, until in lat. 40° N they may occur as frequently as 10 days per month in winter. Typical tracks followed by the temperate cyclonic depressions are shown in Fig. 40. Most of the depressions affecting the main and southern islands of Japan have their origin in China. As will be seen from the diagrams they are most frequent from December to June and are rare in July, August and September. The summer depressions rarely produce strong winds; most of the gales occur as a result of winter storms. Near the coast the gale winds are from a direction north of west, for the cyclonic circulation is reinforced in rear of the centre by the strong outblowing monsoon. Further out to sea the gales are often from south of west. In the belt of prevailing westerly winds gales become increasingly frequent with increasing latitudes (Table III, p. 96)—figures for Auckland and Tatoosh island.

Free Air Winds

Figs. 41–4 show that the prevailing wind, as shown by the average drift of middle level clouds, is everywhere towards the west. Within 10° of the equator easterly winds continue to prevail at all heights up to at least 16,000 ft., though even on the equator (at Nauru)

westerly winds occur occasionally (33% of winds at 6,000 ft.). In higher latitudes, however, an upper westerly wind (counter-trade) makes its appearance and becomes progressively more frequent, especially in winter, and is found at progressively lower levels as the region of the surface westerlies is approached. At Pearl harbour (20° N) the easterly winds prevail up to great heights in summer, but in winter a counter-trade occurs from a westerly direction above 10,000 ft. This is also recorded from Midway (8° N). At Tutuila in Samoa (14° S) there appears to be a definite counter-trade current at 16,000 ft.

The westward drift at middle heights is almost universal; but, during the summer monsoon of the northern hemisphere, there is a strong northward flow of air at these levels in the Western Pacific from the southern hemisphere towards the Asiatic low-pressure centre. No such diversion occurs during the winter monsoon, when the air at middle levels appears to flow westwards, over-riding the shallow current of the southward flowing winter monsoon. Winds increase in force up to 3,000 ft. and then decline steadily (Table IV, p. 97). Three-quarters of the winds are less than 15 knots (Beaufort force 4); gale winds of 28 knots (Beaufort force 7) or over are rare, occurring chiefly in winter at heights of 1,500 ft. to 3,500 ft.

TEMPERATURE

Figs. 45 and 46 show the January and July mean temperatures of the sea surface and of the air above the open sea. The air temperatures are based on the night-time observations (2100 hr. to 0300 hr.); the day temperatures would be only very slightly higher. The temperature of the air is slightly lower than that of the sea because the trade winds constantly bring cooler air from lower latitudes. The eastern side of the ocean is colder than the western, because of the volume of cold water imported by the currents and winds setting equatorwards along the coasts of North and South America, and because the trade winds sweep the warmer surface waters continually across the ocean from east to west.

Within the tropics the variation of temperature throughout the year is so slight as to be negligible. The average temperature in the coldest month is seldom less than 78° F. or in the hottest month more than 82° F.

At the tropics the range has increased to about 8° F. (70° to 78° F.),

and by 40° N or 40° S it may be 10° F., but is usually less. Island stations have a slightly higher range than the open sea, e.g., Midway (28° N) has a minimum in February (65° F.) and a maximum in August (78° F.). It is only where monsoon influences are felt that the temperatures fall below 50° F., e.g., at Kagoshima (February 45° F., August 80° F.). Winters here are unduly cold owing to the strong flow of polar continental air from the Asiatic mainland. The range of sea temperature is also large in these parts because the

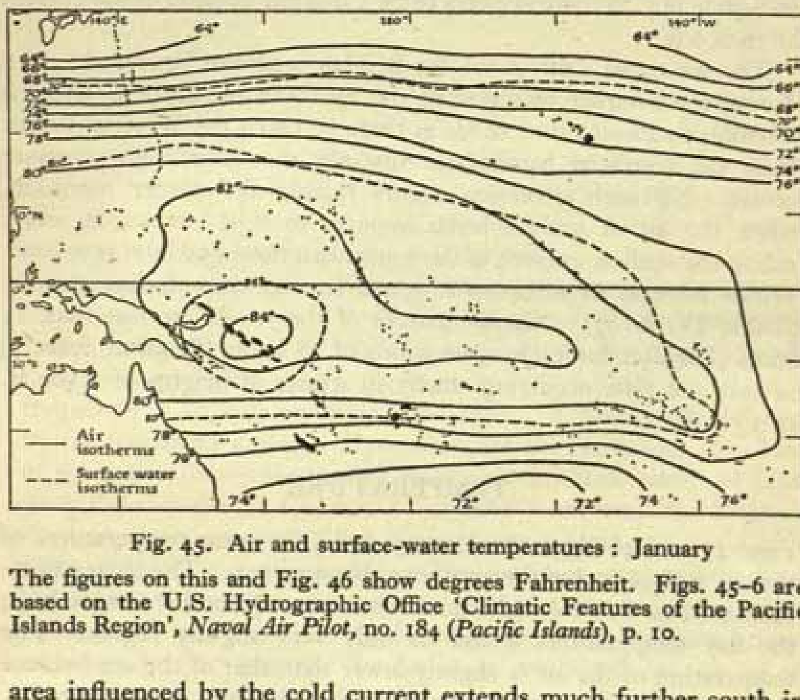

Fig. 45. Air and surface-water temperatures : January

The figures on this and Fig. 46 show degrees Fahrenheit. Figs. 45–6 are based on the U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), p. 10.

area influenced by the cold current extends much further south in winter. The range of sea surface temperature off the southern islands of Japan is from 60° F. to 80° F., while in the Tsugaru straits it ranges from 40° F. (Oya Shio water) to 68° F. (Kuro Shio water). Along the Kurile islands the sea temperature is near 32° F., and pack ice is experienced near the coast in the area affected by the cold Kurile current. The range of air temperature, like that of sea temperature is considerable in Japan. At Tokyo it ranges from 37° to 78° F. and at Nemuro, the most easterly point on Yezo, from 22° to 63° F. It will be noticed that, though winter temperatures are very low for their latitude, summer temperatures in and off

Japan are high because the wind is from the south-east, off the warm waters of the Kuro Shio.

The diurnal range of temperature is very small over the open ocean between the tropics and is small at island stations (usually about 8° F.). It is sufficient, however, to produce land and sea breezes which are described above. It increases with latitude; Hilo has a mean daily range in April of 13.5° F. (minimum) and in February of 15.5° F. (maximum). In the monsoon region of Japan it is greater still (Tokyo, 17.6° F. in January, 12.9° F. in July). This is the only place below 40° latitude where extremes of heat and cold are experienced (Tokyo has recorded 98° F. and 15° F.) and

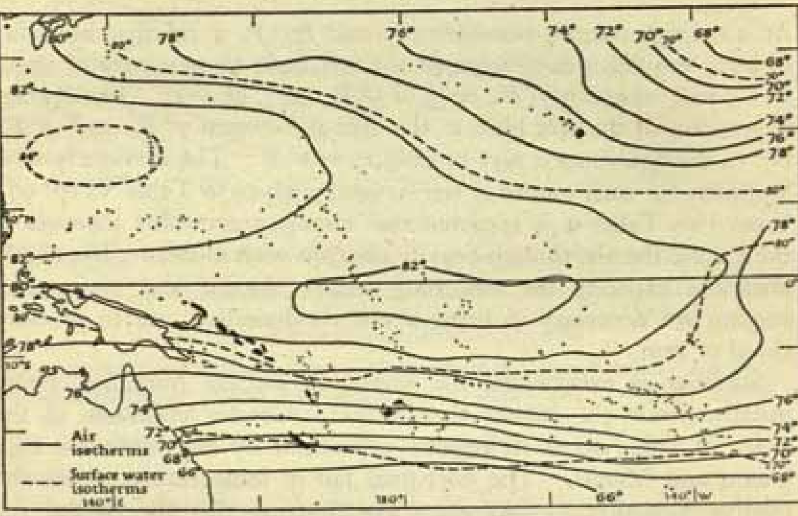

Fig. 46. Air and surface-water temperatures: July

For explanation and source see Fig. 45.

where freezing point is reached or surpassed. On the islands within the tropics the thermometer never reaches 100° F. or falls below 50° F. (Table V, p. 98).

The occurrence of heavy rains drives down the temperature; in the monotonously hot climates of the equatorial zone the thermometer may descend 12° F. to 15° F. in half an hour from this cause.

Many of the islands rise to considerable heights and some of them have fair-sized areas where the temperature is profoundly modified by this fact. In calculating the temperatures to be expected at high levels the usual formula (3° F. decrease per 1,000 ft.) works quite

well, as is shown by the figures for Nandarivatu, in Fiji, and for Volcano Observatory and Humuula, both in the island of Hawaii.

Monthly Temperatures

Station	Height in ft.	J	F	M	A	M	J	J	A	S	O	N	D	Year
Humuula	6,680	50·0	50·4	48·6	49·0	51·5	53·0	54·7	55·6	54·5	54·4	52·0	51·3	52
Volcano Obs.	3,937	57·8	58·6	59·0	59·4	61·0	62·0	62·8	63·4	63·2	62·8	60·6	59·2	60·8
Nandarivatu	3,002	69·4	69·0	68·4	67·2	66·4	66·0	65·6	65·4	65·7	66·6	67·8	68·6	67·2

HUMIDITY

At air temperatures between 70° and 80° F. a relative humidity of 65% implies a depression of the wet bulb temperature of about 8° F., 70% of about 7° F., 80% of 5° F., 90% of 2° F. The average depression of the wet bulb in the area is between 7° F. and 3° F., but in the doldrums it may be only 1° or 2° F. The average relative humidity for each month at ten stations is given in Table VI (p. 99). From this Table it is apparent that almost everywhere throughout the Pacific the air, though heavily charged with moisture, has nearly always a capacity for absorbing more. Ascent and consequent cooling are necessary to bring about condensation and to produce cloud or rain.

Summer is everywhere the season of highest humidity, being usually about 5% higher than winter. Greater contrasts, of the order of 10%, occur in regions influenced by the monsoon, e.g., Guam and Manila. The nocturnal fall of temperature causes the relative humidity to increase. To illustrate this the figures for Honolulu, Guam, and Afiamalu (an unusually humid station 2,000 ft. above sea level in the Samoa group) are given for morning, noon and night in Table VI. The humidity is 8% or 12% less in the middle of the day than at night. The figures for Guam (0600 hr.) and Honolulu (2000 hr.), however, show that even at night the air near sea level is far from saturated at most islands.

In consequence of these low humidities the central Pacific is a region of low cloudiness, averaging about 5/10, cumulus being the commonest type (Fig. 47). The islands in general show a higher cloudiness than the open sea, especially by day. This is to be expected, as the lower islands set up convection currents during the day, resulting in an afternoon maximum of cumulus or cumulonimbus cloud, while the higher islands force ascent of the air. Many

of the higher islands in the trade winds have an almost permanent cloud cap caused in this way. The cloud cap dwindles and may disappear if the wind drops (vol. II, pp. 308). The lowest cloud amounts (4/10) occur in the areas under the influence of the tropical

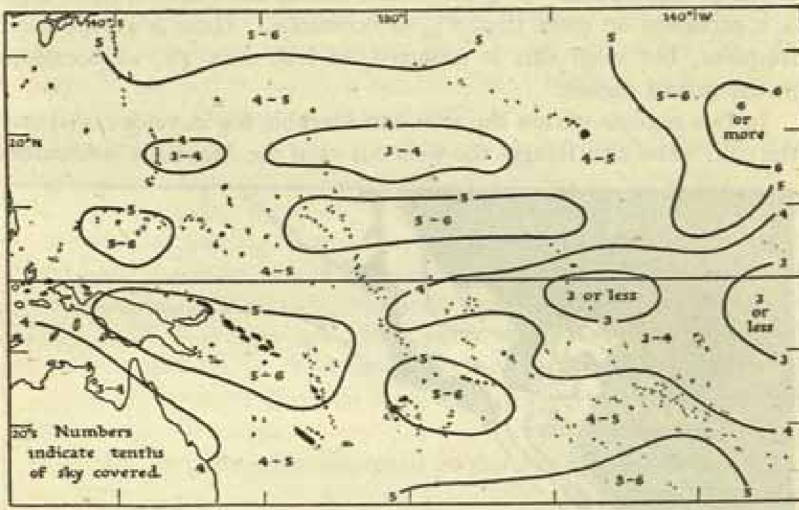

Fig. 47. Average annual cloud amount

This figure has been computed from ships' estimates. In general the amounts of cloud reported for island stations are higher than those observed over the open sea. Based on the U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), p. 52.

anti-cyclones. Cloud increases towards the doldrums where it exceeds 6/10 and (in summer) towards the west where the monsoons occur and the cloud amount also exceeds 6/10. The highest cloud amount occurs off the Peruvian coasts (7/10) and is due to the cold waters of the Peruvian current. The Pacific and its islands thus enjoy, on the whole, a sunny climate, experiencing 50% to 60% of the possible number of hours. The average duration of sunshine is given below (in hours).

Station	Latitude	J	F	M	A	M	J	J	A	S	O	N	D	Year
Honolulu	21° 18′ N	201	209	219	226	257	258	270	274	249	244	202	196	2,805
Saipan	15° 14′ N	186	167	239	261	263	258	175	222	168	184	207	199	2,529
Manila	14° 35′ N	173	205	224	257	215	162	132	130	134	157	156	148	2,103
Palau	7° 20′ N	172	187	227	211	182	185	146	176	188	170	192	169	2,205
Apia	13° 48′ S	142	153	172	188	197	187	204	223	218	204	175	158	2,221
Suva	18° 08′ S	196	165	170	156	125	130	152	132	144	163	168	208	1,909

VISIBILITY AND FOG

In the open ocean between the tropics visibility is generally good and often very good. Days of 'exceptional visibility' exceed one in ten in many parts. Fog is rare and hardly anywhere in these areas is it recorded on more than 2% of occasions. Haze is a little more frequent, but even this is reported on less than 3% of occasions in the inland region.

In two regions within the area considerable fog develops: (i) over the cold water that fringes the west coasts of the Americas in latitudes

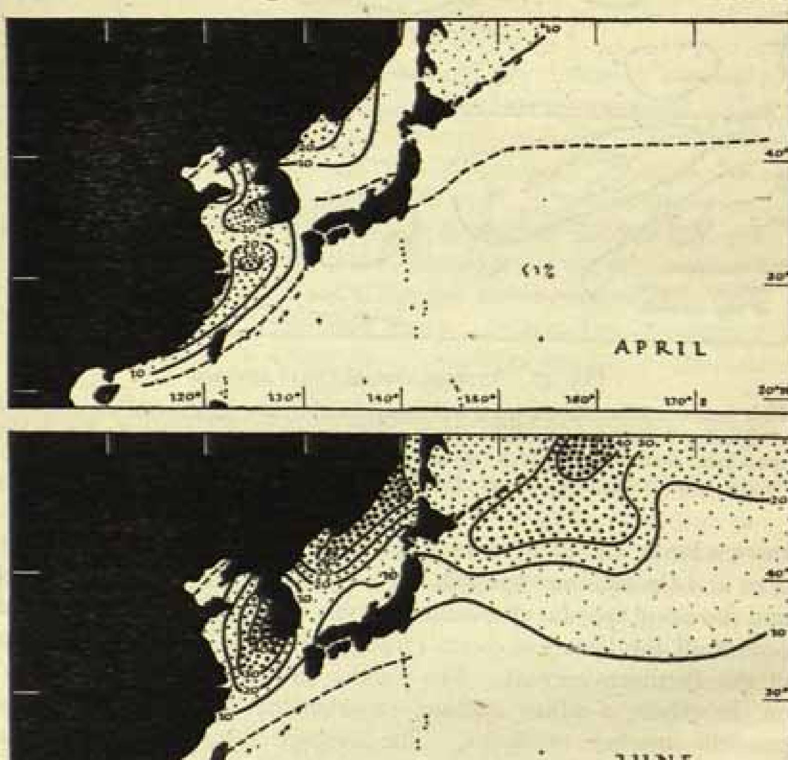

Fig. 48. Percentage frequency of fog over the sea in the north-west Pacific

The pecked line represents a frequency of 1%. Areas where the frequency exceeds 10% are stippled according to percentage frequency. Based on the Air Ministry Meteorological Office, *Weather in the China Seas and in the Western Part of the North Pacific Ocean*, vol. 1, pt. 1, pp. 148–9 (London, 1938).

30°–50° N and 15°–40° S; (ii) off Japan, where the cold waters of the Oya Shio or Kamchatka current chill the southerly winds in summer. This is one of the foggiest regions of the world, rivalling the Newfoundland banks. The foggiest region is off the Kurile islands, where fog is recorded on 40% of occasions in June. The area affected extends further south in the months of calmer weather (April and May) before the monsoon has gathered force. Fig. 48 shows the percentage frequency in April, when the fog is furthest south, and in June, when it is most severe further north.

Along the coasts of North and South America, washed by the cold currents, the frequency of fog is high (San Francisco has thick fog—visibility less than 1,000 ft.—on 19 days in the year, Eureka on 51 days), but the fog does not extend very far out to sea. Juan Fernández, however, nearly 400 miles from the coast, has fog on 25 days a year. The high humidity in these regions causes cloud to form readily at fairly low levels where the air is forced to ascend, as, for example, in the Galápagos, where it is known as the *garúa*.

Figures for some stations in these foggy regions are given in Table VII (p. 100).

Fog may be practically neglected in the central Pacific.

RAINFALL

The principal types of rainfall between lats. 30° N and 30° S can be classified as follows:

1. Convectional rain in the doldrum belt of convergence of trade winds. This lies generally north of the geographical equator, especially in the Eastern Pacific. Its annual migration has been described above, and the rainy season is, in general, the season when it covers the particular station. The rainiest parts of the Pacific, e.g., the Caroline and Marshall islands, derive most of their precipitation from this cause.

2. Orographic rain from the trade winds. This occurs all the year round but is apt to be heavier in winter than in summer because the trade winds are then stronger. It is characteristic of the higher islands on their windward side. Striking contrasts of rainfall occur for this reason on the windward and leeward sides of high islands such as those of New Caledonia, Fiji, Samoa and the Hawaiian islands. Waiawa (22 in.) and mount Waialeale (476 in.), both on the island of Kauai, may be taken as the driest and wettest stations in the whole of the Pacific.

3. Typhoon or hurricane rain, occurring during the hurricane season (pp. 68–71). It can be excessive while it lasts, but is infrequent at any one station. In higher latitudes rain is due to depressions of temperate origin. This affects the coasts of China and Japan in fairly low latitudes during winter, but elsewhere is not usual below 30° N or S. In the Lower Cook islands (lat. 20° S) some of the winter rain comes on westerly winds which are probably related to depressions, though this is generally the drier season. At Norfolk island in 29° S, winter rain predominates, as it does in New Zealand. Midway has some depression rain in winter, while the *kona* (meaning leeward or south-west) rains of the Hawaiian islands occurring in the winter half-year, though of short duration are very heavy. On the lee side of the islands (as regards trade winds) the rainfall is normally very light, but a single *kona* rain storm, associated with a

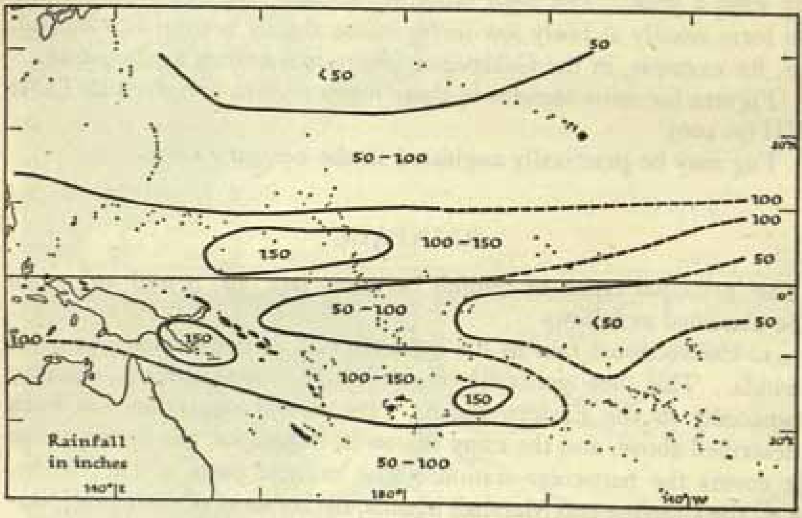

Fig. 49. Generalized annual rainfall

The isohyets are based on the average values for annual precipitation available for stations where consistent measurements have been made over a number of years. Based on the U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), p. 59.

depression to the north, may exceed the normal annual total. The smallness of the annual average, however, shows that *kona* rain is exceptional.

Because of the variety of altitude of the islands and the conse-

quent contrasts in the amount of orographic rain it is difficult to construct isohyetal maps, but Fig. 49 gives a general picture of the annual distribution of rain.

The heaviest rainfall, in many places exceeding 150 in., occurs along the equator on the western side of the ocean, including the Carolines and New Guinea. This belt of heavy rain branches to the east into a northerly belt between 5° and 10° N (including the Marshall islands and Fanning) and a southerly branch between 10° and 20° S (including the Solomon islands, Ellice islands and Samoa). Between these two arms there occurs, on and just south of the equator, a remarkable wedge of low rainfall, with less than 100 in. or, further east, less than 50 in. of rain. It includes Howland, Baker, Malden, Christmas, Jarvis, the Phoenix islands and extends eastwards to the Galápagos and the dry border of South America. Rainfall is, however, very variable in this wedge, and long wet spells may be experienced, during which the rain resembles that of the wet zones to north and south. Polewards from the wet belts described above, the rainfall diminishes towards the high pressure regions of the horse latitudes, but the decrease of rain is much less marked in the southern hemisphere than in the northern. Midway and Honolulu (lee side of Oahu) have less than 50 in.; no stations in the south show such low values.

Seasonal Distribution of Rain (*Table VIII, p.* 101)

Nowhere in the central Pacific is there a true dry season if monthly averages are considered, but this does not mean that droughts of considerable duration are not experienced. On many of the islands the rain is unreliable and may fail in the drier season, so that long droughty spells occur. In the equatorial wet belt rain is heavy at all seasons. But as we go north or south into the trade wind zones, a drier season begins to appear; this is generally 'winter' or 'spring' in either hemisphere, the wettest season being usually late 'summer' or 'autumn'. Towards the poleward margin of the trade wind zone the rain is more evenly distributed throughout the year and even tends eventually to have a winter maximum (e.g., in the Hawaiian islands). Still further from the equator the winter maximum is emphasized by the oncoming of winter depression rain belonging to the edge of the depression belt.

West of 150° E and north of the equator the effect of the proximity of Asia is felt, and the regime is clearly abnormal, resembling that of south China. Subject to numerous exceptions we can there-

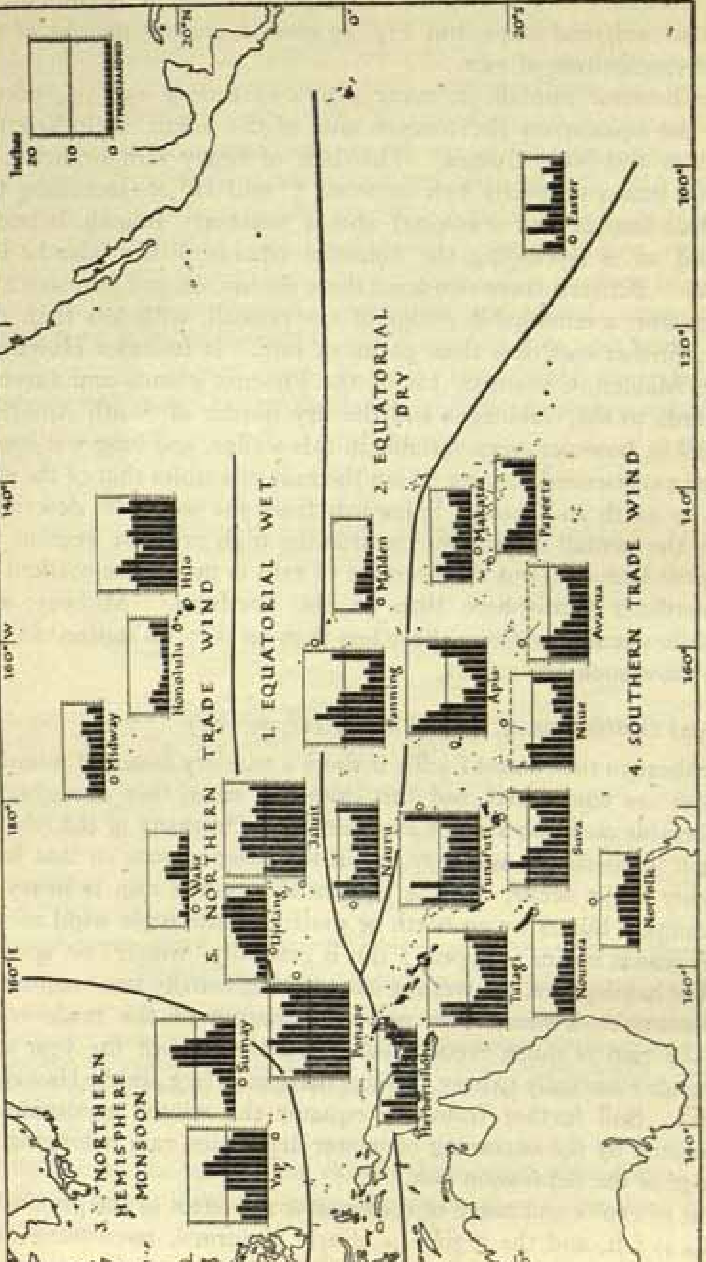

Fig. 50. Rainfall regimes and zones of the Pacific

The regions show the broad limits of rainfall regimes. Based on various sources.

fore recognize five rainfall regimes as follows. Their distribution and approximate limits are set out in Fig. 50.

1. Equatorial wet zone. Rainfall is heavy in all months and there is no dry season (e.g., in Jaluit).

2. Equatorial dry zone. Rainfall is light and very unreliable. The dry season is from September to December, and the wet season from March to May (e.g., in Malden island).

3. Monsoon regime of northern hemisphere. The winter is relatively dry with a summer maximum. There is usually a slight falling off in July or August (e.g., at Naha).

4. Southern hemisphere trade wind zone. Here is a late summer or autumn maximum, and a winter or spring minimum (e.g., at Papeete).

5. Northern hemisphere trade wind zone. The seasonal variation is slight, but there is a tendency to a winter maximum (e.g., in the Hawaiian islands).

Intensity and Nature of Rainfall

The figures given in Table IX (p. 102) show that the amount of rain occurring on each day that rain falls is relatively high, exceeding 0·4 in. at most stations. The rate of fall is lowest at lee stations

Variability of Rainfall

	Honolulu XII–II	Jaluit III–VII	Fanning II–V	Ocean I XII–II	Malden III–V	Avarua I–III	Apia XII–II	Suva II–IV
No. of years' observations	30	18	21	27	20	30	30	30
No. of years with 2 in. per month	30	0	17	24	20	23	19	30
% of years with 2 in. per month	100	0	81	89	100	77	63	33
No. of years with 1 in. per month	30	0	14	21	18	12	9	4
% of years with 1 in. per month	100	0	67	73	90	40	30	13
No. of years with 2 in. in 'wet season'	19	0	4	11	12	2	0	0
% of years with 2 in. in 'wet season'	63	0	19	41	60	7	0	0
% variability of rain	30	9	38	48	72	18	16	16

Figures in roman type beside the names of stations indicate the months of the wet season.

like Honolulu (0·2 in.) where the total rainfall is low, and highest at stations in the equatorial wet zone (e.g., Jaluit). It increases with altitude (e.g., compare Honolulu and Tantalus; Wailuku and Kaenae valley; Apia and Afiamalu). Added intensity is not, however, solely responsible for the increase of rain with altitude, rain is more frequent as well as heavier at high-level stations.

The most torrential rain is associated with tropical storms which will often produce 12 in. in 24 hours; 24 in. is not uncommon and Baguio, in the Philippines, once had 46 in. Orographic rains are often very heavy and continuous. The *kona* rains of the Hawaiian islands (p. 82) also give very heavy individual falls.

The figures quoted above show that periods of drought (months with less than 1 in. of rain) may occur quite frequently on all but the wettest islands in the equatorial wet zone (such as Jaluit), and in its southern extension (as at Apia and Suva). They also show that even in the wet season rains may fail to appear. December is the wettest month at Honolulu, with an average of over 4 in., but in fifteen out of fifty years between 1886 and 1935 the rainfall has been less than 2 in. At the other extreme 16 in. was recorded in 1927. Rainfall throughout the whole of Oceania is extremely variable. The greatest variations are found in the equatorial dry zone and on its borders. Ocean island had 178 in. in 1919, but only 14 in. in 1917. Malden had 94 in. in 1914, but only 4 in. in 1908. In the 21 years 1891–1918, 6 years at Malden had less than 10 in., and 5 years had more than 40 in. Figures of mean annual rainfall in such a climate have no meaning (vol. II, pp. 458–9). In this region, which lies between the trade winds of the two hemispheres, rain is usually scanty with east or south-east winds, but when the wind drops or shifts to the west rain usually occurs, often very heavily. Fanning island lies in the trade wind zone for part of the year and is relatively dry from September to November but comes into the calms from December to May (Table I, p. 91), when it has its wet season. In some years, however, such as 1907 and 1923, the trade winds affected the island for most of the year and rains were scanty.

The transition from the wet zones to the dry zone is very abrupt, and the change-over takes place in a very small distance from north to south. But although the boundary is normally about 2° or 3° N of the equator it shifts with the seasons, though still remaining abrupt. Thus at Christmas island and Malden (Table VIII, p. 101) the rains suddenly fall off in June as the dry conditions supervene

and begin abruptly again in January at Christmas island and in March at Malden. The movement of the boundary, however, is not reliable and regular, hence there arises great variability near the boundary—e.g., in the southern Marshall islands. Table X (p. 103) shows the month-to-month occurrence of rain at Ocean island and emphasizes the remarkable contrasts. Every month has in one of the 27 years exceeded 12 in., yet every month, except July and August, has at some time had less than one-third of an inch, and these two months have fallen below 1 in. at one time or another. The boundary between the dry zone and the rainy region of the south-east trades is also debatable; the Marquesas lie near the transition line.

Thunderstorms

In the central Pacific these are associated with the doldrum belt and are most frequent in the season of calms in late summer, which is also the rainy season. The rain of this season is mainly of the instability type and the instability of the atmosphere is often sufficient to produce thunder, mostly at night or in the early hours of the morning. North of 15° N and east of 140° W thunderstorms are rare, but they become more frequent towards the south-west and are most numerous in New Guinea and the Solomon islands, where they may be expected on 10 per cent. to 15 per cent. of occasions. Frequencies for twelve stations are given in Table XI (p. 104).

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CLIMATIC TABLES

I. *Percentage frequency of wind directions*

(i) Honolulu, Oahu (21° N, 158° W), 1905–30

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	7·2	38·5	27·2	4·5	6·7	8·9	3·8	2·8	0·4
F	7·4	38·7	27·0	4·2	6·4	9·4	3·7	2·8	0·4
M	7·3	40·2	31·1	4·8	4·7	6·1	3·0	2·4	0·4
A	4·2	47·1	35·4	3·3	3·7	3·1	1·7	1·3	0·2
M	2·7	54·4	40·8	3·1	3·1	3·3	1·5	0·7	0·4
J	1·6	43·6	48·4	1·7	2·0	1·7	0·5	0·3	0·2
J	0·9	43·4	52·1	1·5	0·9	0·5	0·3	0·3	0·1
A	0·9	44·7	49·9	1·5	1·1	0·9	0·4	0·3	0·3
S	2·0	43·0	47·2	2·1	2·8	1·6	0·6	0·6	0·1
O	3·5	43·8	40·6	2·7	3·4	3·6	1·1	0·7	0·6
N	5·8	45·8	34·9	2·8	3·9	3·5	1·7	1·2	0·4
D	6·8	38·9	33·7	5·0	4·7	5·5	3·0	2·2	0·2

(ii) Midway (28° N, 177° W), 1917–24

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	8	17	11	9	10	20	9	16	0
F	5	14	7	11	7	24	11	21	0
M	6	23	16	17	5	14	6	13	0
A	11	43	20	10	4	3	4	5	0
M	6	34	10	15	8	6	8	10	3
J	5	30	10	23	9	8	5	6	1
J	1	45	27	14	6	3	3	1	0
A	3	46	34	13	3	0	1	0	0
S	3	35	18	28	3	5	4	3	1
O	8	46	15	7	3	6	7	7	1
N	8	32	13	10	4	10	8	14	1
D	5	18	8	9	7	18	14	21	0

(iii) Guam (13° N, 145° E), 10 years

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	4	79	15	1	1	0	0	0	0
F	5	72	17	3	1	0	0	1	1
M	5	65	27	2	1	0	0	0	0
A	2	52	36	5	2	0	0	1	2
M	3	44	33	8	3	2	1	1	5
J	4	30	39	9	3	4	2	1	8
J	3	19	21	20	15	9	4	3	6
A	5	19	11	14	17	19	6	4	5
S	6	19	12	8	13	19	9	6	8
O	6	30	16	13	12	8	5	3	7
N	4	53	28	8	2	1	1	1	2
D	1	72	20	4	2	1	0	0	0

(iv) Yap (10° N, 138° E), 1906–30

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	2	72	21	1	0	0	0	0	4
F	3	75	17	1	0	0	0	0	4
M	5	69	18	2	1	0	1	1	3
A	3	58	24	2	1	2	1	1	8
M	3	39	32	5	3	2	2	1	13
J	5	26	27	8	5	6	4	2	17
J	7	14	12	9	7	16	11	5	19
A	6	7	4	4	8	28	22	5	16
S	8	10	7	5	8	19	16	7	20
O	7	18	10	4	6	15	14	8	18
N	9	40	19	5	4	4	4	4	11
D	3	54	26	6	2	3	2	0	4

(v) Jaluit (6° N, 170° E), 1892–9

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	2	67	18	7	1	1	0	0	4
F	2	61	24	9	1	0	0	0	3
M	0	63	24	8	1	0	0	0	4
A	2	44	35	12	2	0	0	0	5
M	1	39	38	9	2	1	0	1	9
J	1	45	36	7	2	1	1	0	7
J	1	33	32	13	2	1	0	2	16
A	0	31	31	15	4	2	1	1	15
S	1	15	20	28	10	3	1	1	21
O	4	15	27	30	6	4	2	2	10
N	5	35	28	19	3	2	0	1	7
D	2	63	21	8	1	1	0	0	8

(vi) Fanning (4° N, 159° W), 1903–18

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	1	18	22	57	1	0	0	0	1
F	1	25	35	38	1	0	0	0	0
M	1	36	43	20	0	0	0	0	0
A	1	34	45	17	1	0	0	1	1
M	2	25	44	19	4	1	0	1	4
J	2	12	36	41	4	2	0	1	2
J	0	5	30	55	5	1	1	0	3
A	1	2	23	64	3	1	0	1	5
S	0	3	24	64	5	1	0	2	1
O	1	2	15	68	6	5	1	2	0
N	0	5	28	57	1	3	1	2	3
D	1	15	31	50	0	0	0	2	1

(vii) Malden (4° s, 155° w), 1910–19

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	8	20	52	11	1	1	2	3	2
F	4	31	53	7	0	0	1	3	1
M	7	37	40	7	0	1	1	4	3
A	6	23	41	17	0	1	1	4	6
M	3	27	45	21	0	1	0	1	2
J	2	17	54	26	0	0	0	0	1
J	0	10	56	31	1	0	0	1	1
A	1	13	55	30	0	0	0	0	1
S	1	14	52	32	0	0	0	0	1
O	1	18	46	28	1	0	0	2	4
N	4	25	46	21	0	0	0	3	1
D	3	29	49	14	0	2	1	1	1

(viii) Makatea (16° s, 148° w), 1910–13

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	9	16	30	2	1	2	7	10	23
F	11	19	19	2	1	2	8	10	28
M	5	15	41	7	0	1	1	7	23
A	6	9	31	16	1	0	0	8	29
M	10	12	25	26	2	0	0	4	21
J	2	14	48	15	0	1	0	1	19
J	2	10	54	10	1	2	1	1	19
A	2	7	47	22	3	1	0	1	17
S	1	12	55	15	2	0	0	0	15
O	2	12	52	13	2	1	1	2	15
N	3	16	47	10	0	0	0	5	19
D	8	16	40	12	0	0	1	6	17

(ix) Rarotonga (21° s, 159° w), 1929–33

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	13	20	22	17	12	4	3	3	6
F	4	18	33	14	12	3	5	6	4
M	5	14	27	17	14	5	4	8	5
A	3	12	29	15	19	6	4	4	9
M	3	12	24	17	23	6	5	2	8
J	10	10	19	15	20	10	4	5	5
J	8	11	20	11	18	8	10	4	10
A	7	10	21	23	17	8	7	4	4
S	3	12	30	18	16	5	8	2	4
O	7	14	28	30	11	3	1	2	3
N	7	17	29	22	18	3	1	3	1
D	10	22	24	16	14	4	3	6	3

(x) Apia, Samoa (14° S, 172° W), 1906–08

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	3	9	17	27	24	16	2	2	0
F	1	4	14	17	11	26	15	7	5
M	6	9	12	25	17	12	5	11	3
A	2	13	23	32	11	7	5	6	1
M	2	15	42	27	6	3	1	2	2
J	1	13	47	30	5	1	0	0	3
J	1	17	38	30	8	1	0	1	4
A	1	13	60	20	4	0	0	1	1
S	1	22	50	23	4	0	0	0	0
O	2	28	33	33	12	1	1	0	0
N	4	16	29	27	14	4	3	3	0
D	4	15	24	29	16	5	3	4	0

(xi) Suva, Fiji (18° S, 178° E), 33 years

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	10	21	27	24	4	6	2	2	4
F	13	19	29	19	5	3	2	3	7
M	13	21	25	17	4	7	3	2	8
A	9	19	28	25	4	5	1	2	7
M	8	15	25	30	5	6	1	3	7
J	8	14	25	30	4	3	2	5	8
J	9	17	23	31	6	3	2	3	6
A	6	14	28	29	5	7	1	4	6
S	6	17	27	35	4	4	2	2	3
O	5	16	35	30	5	3	1	2	3
N	5	16	35	29	6	4	1	1	3
D	8	14	31	28	5	5	3	3	3

(xii) Norfolk (29° S, 168° E), 12 years

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	7	9	32	23	10	6	6	5	2
F	5	13	34	26	9	3	3	4	3
M	3	6	28	37	15	4	2	2	3
A	8	11	25	24	11	6	7	4	3
M	7	8	20	17	12	12	14	7	3
J	8	10	8	12	9	14	23	12	4
J	6	3	11	14	13	21	22	7	3
A	5	8	15	15	14	15	16	8	4
S	12	9	15	14	11	14	13	10	2
O	11	11	13	16	11	15	13	7	3
N	11	4	14	26	12	10	10	9	4
D	14	12	23	22	10	6	6	5	2

(xiii) Easter island (27° s, 109° w), 1911–13

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	13	13	24	15	4	2	7	9	13
F	10	15	25	25	5	0	2	9	9
M	6	13	35	20	2	2	7	6	9
A	15	9	12	25	8	2	5	6	18
M	11	9	14	15	11	2	14	16	8
J	11	3	9	16	22	10	12	11	6
J	14	6	12	9	19	10	8	11	11
A	16	14	14	10	12	8	8	10	8
S	13	5	14	13	17	9	8	12	9
O	15	7	12	27	12	3	5	7	12
N	21	5	15	25	13	4	4	3	10
D	7	8	22	28	12	3	6	4	10

(xiv) Juan Fernández (34° s, 79° w), 19 years

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	calm
J	0	0	1	22	34	18	3	4	18
F	0	0	1	20	35	12	5	6	21
M	1	0	0	18	36	14	5	6	20
A	2	2	2	16	20	14	11	10	23
M	2	1	2	13	22	13	13	13	21
J	5	16	5	9	14	21	8	12	10
J	4	14	6	12	14	21	6	13	10
A	1	2	1	13	24	17	11	8	23
S	1	2	1	14	26	15	10	9	22
O	0	1	2	12	30	22	6	5	22
N	1	1	1	16	26	19	7	6	23
D	1	1	1	17	31	17	6	4	22

Based on: (1) G. Schott, 'Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, pp. 99–101 (Berlin, 1938); (2)—for Juan Fernández—U.S. Hydrographic Office *Sailing Directions for South America*, vol. III, p. 440 (4th edition, Washington, 1938).

II. *Percentage frequency of surface winds of different velocity*

Station or Square	Period	Velocity in knots				
		0–3	4–14	15–28	29–41	over 41
Pearl harbour, Oahu	May–Oct.	13·3	66·5	20·1	0·1	—
	Nov.–June	18·2	64·7	16·7	0·4	—
Sumay, Guam	July–Oct.	34·8	63·9	1·3	—	—
	Nov.–June	17·9	80·0	2·1	—	—
Palau	Sept.–Oct.	43·8	56·2	—	—	—
	Nov.–Dec. and Feb.–May	44·0	55·0	1·0	—	—
Apia, Samoa	Apl.–Nov.	31·8	68·2	—	—	—
	Dec.–Mar.	48·2	51·8	—	—	—
Square 20°–25° N, 155°–160° W	May–Oct.	6·6	67·2	25·8	0·4	—
	Nov.–Apl.	17·7	51·3	30·0	1·0	—
Square 15°–20° N, 150°–175° E	July–Oct.	3·8	54·7	39·6	1·9	—
	Nov.–Jan.	—	54·6	45·4	—	—
Square 10°–15° N, 130°–150° E	July–Oct.	3·1	69·6	27·3	—	—
	Nov.–June	—	68·7	31·3	—	—

Based on U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), pp. 34-51.

III. *Number of days with gales (28 knots or over)*

	J	F	M	A	M	J	J	A	S	O	N	D	Year	No. of years observations
Apia, Samoa	2	1	2	—	—	—	—	—	—	—	—	—	5	9
Suva	0·1	0·1	0·2	—	—	—	—	—	—	—	—	0·4	0·5	46
Rabaul, N. Britain	0·6	0·4	0·7	0·5	0·1	0·1	0·1	—	—	0·3	0·5	0·1	3	16
Yap	1	0·8	0·8	0·4	2·0	0·5	0·8	0·3	1	0·7	0·7	1·0	10	4
Ujelang	1·5	0·5	—	—	—	0·3	—	—	—	0·5	0·5	—	3·3	4
Malden	0·6	—	—	0·1	—	0·4	—	0·2	0·1	0·5	—	—	2	10
Fanning	—	—	—	—	0·1	—	—	—	—	—	—	0·1	0·2	14
Futuna, New Hebrides	0·6	0·5	—	0·1	0·3	0·1	—	0·9	0·1	0·1	—	—	3	9
Tulagi	0·5	0·3	0·3	—	0·2	0·8	0·8	0·6	0·5	0·1	—	0·1	4·2	18
Thursday I.	—	—	—	—	—	—	0·1	—	—	—	2	—	3	5
Tonga	0·3	0·3	1	—	—	—	—	—	—	0·5	—	0·5	3	4
Tatoosh I., Washington	19	15	14	10	5	3	2	2	6	12	17	19	124	38
Easter I.	—	—	1	—	—	1	1	0·7	0·7	0·3	—	0·7	5·4	2–3
Auckland (N.Z.)	2	2	2	2	3	3	3	3	3	3	3	3	32	61

Based on: (1) U.S. Hydrographic Office 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*); (2) Admiralty *West Coast of Central America and United States Pilot*, p. 406 (5th edition, London, 1935); (3) Admiralty *Pacific Islands Pilot*, vol. III, p. 243 (6th edition, London, 1931); (4) Admiralty *New Zealand Pilot*, p. 401 (10th edition, London, 1930).

IV. *Average wind velocity in knots at different heights (from pilot balloon observations)*

Station	Surface		1,600 ft.		3,300 ft.		6,600 ft.		9,800 ft.	
	Summer	Winter	S	W	S	W	S	W	S	W
Pearl harbour, Oahu	9·7	8·7	12·3	12·0	13·2	12·2	10·8	10·9	9·6	11·1
Sumay, Guam	4·8	5·9	13·7	18·1	13·6	18·8	12·7	14·3	11·4	12·6
Palau	3·5	3·4	11·6	15·0	12·0	13·7	8·2	9·2	—	8·5
Apia, Samoa	4·0	5·2	10·8	12·2	10·8	11·4	10·2	9·9	10·4	9·5

Based on U.S. Hydrographic Office, 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), p. 32.

V. *Mean, extremes, and range of temperature (in degrees F.)*

Station	Latitude	Mean temperature		Mean extreme		Recorded extreme		Daily range	
		Warmest month	Coldest month	Max.	Min.	Max.	Min.	Jan.	July
Ocean I.	1° 52′ S	81·1	80·8	92	71	96	68	13·1	12·2
Malden	4° 01′ S	82·6	81·5	93	68	99	65	13·6	13·5
Apia, Samoa	13° 48′ S	79·3	77·1	91	65	96	61	9·7	12·1
Guam	13° 24′ N	82·8	78·8	91	69	93	64	8·6	10·3
Honolulu	21° 19′ N	78·4	70·7	86	59	88	52	10·0	9·8
Norfolk	29° 04′ S	71·6	60·6	84	49	89	47	9·9	9·2
Taihoku, Formosa	25° 02′ N	82·4	58·3	97	41	99	32	12·3	16·0
Tokyo	35° 41′ N	77·7	37·4	93	21	98	15	17·6	12·9

Based largely on G. Schott, 'Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T (Berlin, 1938).

VI. *Relative humidity (percentage)*

Station	Latitude	J	F	M	A	M	J	J	A	S	O	N	D	Year
Ocean I.	0° 52′ S	77	77	76	78	75	75	74	73	74	74	75	75	75
Malden	4° 03′ S	70	71	72	74	73	71	69	68	66	66	65	67	69
Yap	9° 29′ S	82	82	81	82	84	85	86	86	85	86	85	84	84
Guam	13° 27′ N													
(0600 hr.)		84	84	84	83	84	85	88	90	89	88	87	85	86
(1400 hr.)		72	71	69	67	68	71	75	78	78	78	76	73	73
Apia, Samoa	13° 48′ S	85	85	85	85	84	83	82	80	81	82	83	83	83
Afiamalu, Samoa	13° 55′ S													
(0600 hr.)		95	95	95	93	93	93	94	94	92	91	93	93	93
(1300 hr.)		87	85	87	87	83	82	83	81	82	81	85	85	84
(2000 hr.)		95	95	96	95	94	93	94	94	93	93	94	96	94
(mean)		92	92	93	92	90	89	90	90	89	88	91	91	90
Manila	14° 35′ N	78	74	72	70	76	81	85	85	86	84	83	81	80
Honolulu	21° 18′ N													
(0800 hr.)		71	70	69	67	66	66	66	67	67	68	70	72	68
(1300 hr.)		64	62	62	62	60	60	60	60	60	62	64	65	62
(2000 hr.)		72	72	71	71	70	70	69	70	70	71	72	73	71
Rarotonga	21° 12′ S	85	84	82	81	75	79	79	74	77	77	79	82	80
Norfolk	29° 03′ S	80	82	82	83	82	82	81	80	81	80	78	79	80

Based on : (1) G. Schott, ' Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, p. 102 (Berlin, 1938) ; (2) C. Braak, 'Klimakunde von Hinterindien und Insulinde', *Handbuch der Klimatologie*, Band IV, Teil R, p. 112 (Berlin, 1931).

VII. *Number of days with fog*

Station or area	J	F	M	A	M	J	J	A	S	O	N	D	Year
Vladivostok	2	[illegible]	4	7	12	15	17	12	2	3	2	2	80
Ocean area, 35°–40° N, 140°–145° E	0	[illegible]	0·3	0·6	1·2	3·6	4	2	0·3	0	0	0	12
San Diego, California	2	3	1	1	1	1	1	1	2	4	3	2	22
Tatoosh I., Washington	1	1	1	1	3	4	8	12	8	5	1	1	46
Arica, Northern Chile	0	0	0·1	0·3	0·1	0	0	0	0·1	0	0	0	0·6
Juan Fernández	2	1·5	1·5	3	3	3	3	2	1·5	1	1	3	25·5
Easter	0	0	0	0·5	3	1	1	0·3	0·3	0·3	0	0	6
Ocean area, 40°–45° S, 120°–125° W	8	11	0	0	8	0	8	0	3	10	6	8	62

Based on various sources.

VIII. *Monthly means of rainfall (inches)*

Station	Height in feet	Period	J	F	M	A	M	J	J	A	S	O	N	D	Year
Summit camp, Kauai	1,870	1910–1924	19·8	9·1	17·9	14·5	13·2	11·1	13·0	12·0	13·3	13·7	15·7	15·8	169
Honolulu	56	1877–1935	3·4	4·0	3·2	2·1	1·4	0·8	1·0	1·2	1·5	1·8	3·4	3·9	27·7
Tantalus, Oahu	1,339	1905–1924	10·2	7·0	9·1	9·0	6·8	6·9	7·4	8·0	7·6	7·0	9·1	11·1	99·2
Kaenae valley, Maui	984	1905–1924	18·6	17·9	22·4	26·1	17·7	16·0	18·6	22·0	18·3	16·5	23·0	25·0	242·1
Hilo	39	1905–1924	13·2	10·5	15·7	13·2	9·2	8·5	9·7	12·4	12·4	11·5	15·7	13·4	145·4
Midway	20	1921–1930	4·3	3·8	3·4	4·4	3·1	2·3	4·1	3·6	5·2	2·5	2·6	2·8	42·1
Guam	62	1906–1922	2·4	3·1	3·2	2·2	4·0	5·7	14·1	15·5	16·3	12·4	7·3	4·7	90·9
Naha, Ryukyu Is.	34	1891–1920	5·3	5·3	6·0	6·3	9·8	10·4	7·1	10·0	7·1	6·7	5·7	4·1	83·8
Manila	46	1885–1925	1·0	0·5	0·7	1·3	4·4	9·9	10·2	16·1	14·4	7·3	5·6	2·4	79·8
Baguio	954	1903–1926	1·0	0·9	1·9	4·5	15·7	19·3	40·1	47·1	31·1	14·8	3·5	1·8	181·7
Koror, Palau	<33	1905–1913	8·6	7·7	7·7	7·0	11·5	12·2	18·0	15·2	11·2	9·6	13·3	15·0	137·0
Palau	105	1924–1929	15·7	8·3	6·8	8·0	17·2	13·1	24·4	15·3	12·9	15·3	10·0	13·7	160·7
Yap	115	1900–1930	7·0	6·8	4·9	5·2	9·6	10·7	16·5	16·3	13·3	11·7	10·2	8·9	121·1
Truk	<33	8 years	7·0	9·1	9·5	11·7	12·2	10·2	13·1	13·3	13·3	10·3	11·4	10·3	131·4
Ponape	<33	1901–1913	11·1	8·8	14·1	19·5	20·0	13·7	16·5	16·1	15·4	15·5	16·5	16·0	183·2
Ujelang	<30	1894–1912	2·1	2·2	2·6	6·2	6·3	7·4	8·5	8·7	10·8	10·1	10·9	4·9	80·7
Jaluit	10	1892–1913	9·6	8·8	14·3	16·4	16·0	15·0	15·2	11·7	13·4	11·9	12·0	13·2	157·5
Fanning	10	1903–1930	10·1	10·9	10·6	13·7	12·3	10·2	8·4	4·5	3·2	3·6	3·1	8·3	98·9
Ocean I.	92	1904–1930	11·8	9·2	7·5	6·1	4·4	4·5	6·3	4·6	4·3	4·3	5·9	9·0	79·7
Kokopo, New Guinea	213	1902–1913	8·0	7·5	8·8	5·5	4·3	5·8	5·9	6·2	4·0	3·3	6·3	7·8	73·4
Tulagi, Solomon Is.	7	1898–1922	13·0	16·5	15·2	10·1	7·5	6·3	7·7	6·8	8·2	8·5	9·6	10·2	119·6
Abaiang	13	1905–1907	13·6	6·0	8·0	11·1	6·5	6·9	6·8	2·9	2·1	10·2	6·7	7·3	88·1
Christmas	<33	1916–1919	6·9	5·4	5·0	4·6	5·5	1·9	2·6	1·1	1·0	0·6	0·3	2·2	37·1
Malden	26	1890–1925	3·4	2·1	4·5	4·6	4·2	2·1	1·9	1·5	0·8	0·9	0·7	0·8	27·5
Papeete, Tahiti	23	1880–1909	8·3	9·2	7·4	4·5	3·3	3·2	1·6	2·0	2·3	3·8	5·5	2·6	60·7
Makatea	128;154	6 years	6·7	8·8	6·1	7·1	3·6	4·8	3·2	4·3	3·6	3·3	5·0	5·5	62·0
Avarua, Rarotonga	23	1899–1935	9·8	10·5	11·5	7·3	5·4	4·4	4·6	4·4	4·5	5·1	6·1	9·2	82·8
Apia, Samoa	10	1890–1932	17·0	16·1	13·5	10·2	6·3	5·2	3·0	3·4	5·0	6·6	10·4	14·0	110·7
Tutuila	—	1900–1921	21·6	24·8	18·7	18·0	15·0	14·6	9·7	7·5	13·1	15·5	19·6	18·6	196·7
Alofi, Niue	69	1906–1935	10·5	11·5	12·7	7·5	4·7	3·0	3·3	4·6	3·9	4·6	5·9	9·0	81·2
Suva	23	1886–1934	11·3	12·0	14·8	12·8	10·0	6·5	5·2	8·1	7·6	8·5	9·9	12·0	118·7
Vila, New Hebrides	—	1905–1912	11·8	8·6	12·7	9·8	4·9	2·4	2·3	2·9	6·7	3·8	11·5	9·1	86·5
Noumea	<33	1860–1914	3·7	5·1	5·7	5·2	4·4	3·7	3·6	2·6	2·5	2·0	2·4	2·6	43·5
Lifu, Loyalty Is.	39	1908–1914	8·6	8·5	9·6	10·4	4·0	3·6	5·4	3·9	3·5	2·6	2·7	2·4	65·2
Norfolk	56	1887–1923	3·5	5·7	3·8	4·3	5·4	5·9	6·3	5·7	4·0	4·0	2·8	3·4	54·8
Kermadec Is.	7	1908	—	6·8	6·9	11·3	6·8	5·9	6·4	9·3	3·9	8·9	—	—	66·2
Easter	98	1911–1913	5·2	1·6	9·0	5·1	3·9	9·5	3·2	2·6	3·5	2·2	5·0	2·9	53·7

Based mainly on: (1) G. Schott, 'Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, pp. 37, 92–8 (Berlin, 1938); (2) C. Braak, 'Klimakunde von Hinterindien und Insulinde', *Handbuch der Klimatologie*, Band IV, Teil R, pp. 102–8 (Berlin, 1931).

IX. *Amount of rain per rain day (inches)*†

Station	Annual rainfall	Number of rain days	Rain per rain day	Height in feet
Makaweli, Kauai	24·4	93	0·26	138
Honolulu	27·7	159	0·18	56
Tantalus, Oahu	99·2	272	0·37	1,339
Wailuku, Maui	28·3	101	0·28	174
Kaenae valley, Maui	242·1	296	0·82	984
Hilo	145·4	279	0·52	39
Midway	42·1	162	0·26	20
Sumay, Guam	90·9	212	0·43	62
Garapan, Saipan	82·8	210	0·40	33
High station, Saipan	97·8	279	0·35	679
Palau	160·7	234	0·59	105
Yap	121·1	259	0·47	115
Ponape	183·2	266	0·69	<33
Lele harbour, Kusaie	176·8	239	0·57	<33
Ujelang	80·7	227	0·36	30
Jaluit	157·5	235	0·67	10
Fanning	98·9	160	0·61	10
Ocean I.	79·7	153	0·51	92
Christmas	37·1	151	0·24	<33
Malden	27·5	88	0·31	26
Papeete, Tahiti	60·7	125	0·48	23
Makatea	62·0	175	0·35	c. 130
Avarua, Rarotonga	82·8	183	0·47	23
Iva, Samoa	129·3	197	0·65	33
Apia, Samoa	110·7	188	0·59	10
Afiamalu, Samoa	189·8	284	0·67	1,969
Neiafu, Tonga	80·8	154	0·53	<33
Suva	118·7	248	0·48	23
Noumea	43·5	130	0·34	33
Norfolk	54·8	149	0·37	56
Easter	53·7	208	0·26	98

† A rain day is, in general, a day on which there was a rainfall of more than 1/100 in.

Calculated from G. Schott, 'Klimakunde der Südsee-Inseln,' *Handbuch der Klimatologie*, Band IV, Teil T, pp. 92–9, 103–4 (Berlin, 1938).

X. *Monthly and yearly rainfall at Ocean island, 1904-30 (in inches)*

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1904	5·6	0·1	0·8	0·2	0·6	1·2	10·2	6·9	3·4	5·3	5·7	14·9	54·9
1905	22·2	20·6	5·7	20·7	10·4	12·5	8·7	4·7	12·4	13·6	9·6	9·0	150·1
1906	13·8	8·9	3·6	0·8	0·3	0·9	1·5	0·6	0·7	0·6	15·6	5·7	53·0
1907	8·6	2·8	7·7	8·8	1·0	2·4	2·8	0·9	1·1	7·6	9·4	5·0	58·1
1908	24·8	10·2	0·1	0·3	1·2	8·7	3·0	3·9	1·1	0·1	0·1	2·0	55·5
1909	2·7	0·4	1·1	0·2	0·6	1·2	5·7	2·4	2·3	0·8	1·0	0·4	18·8
1910	1·3	1·4	0·1	0·04	7·2	2·0	4·6	1·5	1·2	0·7	2·3	6·2	28·5
1911	3·9	6·4	26·2	26·8	5·4	8·5	7·6	4·7	11·2	14·4	7·6	20·8	143·5
1912	23·3	16·5	28·8	12·6	6·8	4·6	4·4	1·3	4·0	11·0	4·3	16·8	134·4
1913	13·6	17·6	1·6	1·3	1·8	0·2	3·4	4·3	5·6	6·4	9·3	12·3	77·4
1914	16·9	12·7	15·0	17·2	15·4	13·0	23·7	8·5	5·9	1·9	9·4	15·2	154·8
1915	14·6	9·4	10·3	13·0	21·7	3·9	1·8	0·6	0·5	0·0	0·2	2·8	78·8
1916	8·6	1·4	0·7	0·1	0·9	0·7	0·7	0·6	0·6	0·3	0·04	0·04	14·6
1917	0·2	0·4	0·1	0·9	0·3	2·5	1·6	0·7	3·3	0·2	0·4	3·8	14·3
1918	0·2	0·5	7·7	1·9	3·9	4·6	19·0	14·3	13·9	4·7	8·7	19·4	98·8
1919	17·0	23·8	21·2	17·7	7·5	8·0	14·3	14·0	13·2	17·6	6·9	13·9	175·1
1920	12·5	16·0	17·1	3·9	5·3	10·3	6·5	1·4	1·2	0·3	0·2	7·2	81·9
1921	16·9	1·7	0·7	0·5	1·0	0·7	3·9	1·3	2·4	1·6	3·3	14·3	48·3
1922	17·4	10·2	0·6	3·1	5·2	2·2	8·2	3·7	1·2	0·04	2·4	1·5	55·7
1923	4·9	5·4	14·4	9·2	0·3	8·6	5·6	17·1	2·0	5·4	11·7	15·8	100·4
1924	31·2	5·1	4·3	0·1	5·1	1·6	2·4	0·9	0·3	2·3	0·2	0·04	53·5
1925	0·5	0·8	1·3	0·04	1·3	5·4	3·9	6·8	2·5	12·6	4·8	8·8	48·7
1926	12·2	14·5	20·1	17·7	11·8	6·9	3·8	6·9	2·3	0·4	4·1	2·0	102·7
1927	0·2	0·2	0·4	0·1	2·2	2·7	6·2	1·7	1·9	0·3	5·8	18·3	40·0
1928	19·5	10·1	0·2	0·8	0·1	1·1	2·6	2·2	2·6	0·7	1·3	3·1	44·0
1929	10·9	21·4	2·1	1·0	4·6	3·5	7·7	9·9	1·1	1·7	13·0	15·4	92·3
1930	21·0	15·2	13·7	2·3	0·2	2·0	8·4	6·5	16·6	7·4	20·3	13·7	127·3
Average	12·0	8·7	7·6	6·0	4·5	4·4	6·4	4·7	4·3	4·4	5·8	9·2	77·9

Based on G. Schott, 'Klimakunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, p. 107 (Berlin, 1938).

XI. *Number of thunderstorms*

	J	F	M	A	M	J	J	A	S	O	N	D	Year	No. of years observation
Midway	1·0	0	0	0·5	0·4	0·2	0·2	1·0	0·2	1·4	0	0·2	5·1	5
Honolulu	1·2	0·6	0·7	0·2	0·4	0·1	0	0·1	0·1	0·2	0·3	0·9	4·8	20
Sumay, Guam	0	0	0	1	0	1	2	2	3	3	3	0	15	5
Yap	1	0·3	1	1·3	1·3	2·0	2·3	3·0	5·7	2·3	3·5	1·7	25·4	3
Jaluit	0·2	0·6	2·0	1·7	2·0	2·2	3·2	2·3	2·3	1·5	2·3	1·2	21·5	5
Fanning	1·7	0·6	3	1·3	2·0	1·4	0·9	0·6	1·1	0·9	1·0	0·9	12·7	8
Ocean I.	1·4	0·5	0·7	0·2	0·2	0·6	0·7	0·2	0·6	0·4	0·6	0·6	6·7	10
Kieta, Solomon Is.	9·0	9·9	11·7	5·3	3·3	3·3	0·3	0·5	2·4	3·7	4·3	6·4	60·1	3–6
Pukapuka, Cook Is.	2·7	4·7	3·8	4·3	2·0	1·7	1·7	0·6	1·6	1·5	4·5	2·7	31·8	7
Aitutaki, Cook Is.	3·0	3·2	6·8	4·2	3·0	1·0	1·0	1·2	0·8	1·4	1·6	4·4	31·6	5
Apia, Samoa	3·5	2·7	3·1	2·6	1·6	1·2	0·4	0·3	0·8	2·3	2·8	3·7	25·0	17
Suva	6	6	7	4	2	2	1	1	1	1	2	5	38	20

Based on (1) U.S. Hydrographic Office, 'Climatic Features of the Pacific Islands Region', *Naval Air Pilot*, no. 184 (*Pacific Islands*), p. 63; (2) G. Schott, 'Klimkunde der Südsee-Inseln', *Handbuch der Klimatologie*, Band IV, Teil T, p. 104 (Berlin, 1938).

Chapter IV

SOILS

Soil Development : Soils and Natural Vegetation : Soils and Agriculture : Soil Erosion : Bibliographical Note

The soils of the Pacific islands are very varied, and important differences exist between those of the 'high' and those of the 'low' islands. In the 'high' islands, especially those which are volcanic, there are often marked differences between the soils of neighbouring areas, both in appearance and in agricultural productivity. There are however certain characteristics, which, speaking very generally, may be said to be shared by most of them. In the first place, they are often loamy or clayey in texture and may become extremely sticky and slippery when wet. In colour they are generally red (a feature which may be noticed in Gauguin's paintings of Tahiti) or yellowish, though in some places the prevailing colour is dark or even blackish. Even in the luxuriant rain forests of Samoa and New Guinea the layer of dead leaves is so thin that the bare surface of the soil often shows through ; the percentage of humus actually incorporated in the surface layers is also small. Besides these visible characteristics, others no less distinctive are shown by chemical analysis. The content of lime and other bases is generally small and in consequence the soil has an acid reaction. Often there is a deficiency in plant nutrients in general. Contrary to what might be expected from the luxuriant vegetation, Pacific soils are by no means always exceptionally fertile.

These features are characteristics not only of the soils of the Pacific islands, but of the moist tropics generally, and to understand why this is so it is necessary to know something about soil development.

Soil Development

Soils are formed by the breakdown or weathering of rocks or other mineral materials, a process which is long and complicated. Climate and parent materials, the plants and animals living in the soil or on its surface, as well as topographical factors such as slope and drainage, all play a part in determining its speed and final result. All these factors are interconnected ; now one, now another, seems

to play the leading part and we are compelled to regard all of them as forming a single very complex system in which no one factor can change without affecting the others. Because the parent rock is only one among a number of factors determining the nature of the soil, a soil map by no means coincides with a geological map; the soil map shows a relation as close or closer to a map of climate or natural vegetation.

Weathering of rocks is of two kinds, mechanical and chemical. In mechanical weathering the rock or other material is split into finer particles by agencies such as frost and sudden changes of temperature. Except on the summits of the highest mountains, frost is unknown in the Pacific islands and diurnal and seasonal temperature changes are usually slight. Such mechanical disintegration as there may be is brought about by small burrowing animals and plant roots which insert themselves into cracks and so split the rocks apart. As in all tropical countries the breakdown of rocks is brought about mainly by chemical changes and in these rain water, with carbon dioxide in solution, plays the chief part.

The most important soil-forming materials in the 'high' islands of the Pacific are volcanic deposits, lava, pumice and ash, and in New Guinea and the neighbouring large islands, old igneous and sedimentary rocks. To a much smaller extent soils are formed from transported materials such as alluvium, wind-blown dust, and wind-blown sand. In all these materials the main constituents are complex silicates which can be hydrolyzed by water into less complex substances, such as simple bases, silica, alumina, kaolin (hydrated aluminium silicate), and iron oxides. These products, in their turn, undergo further changes, while some constituents of the parent rocks, such as quartz (not abundant in most rocks of the Pacific islands) remain unaltered, or weather extremely slowly. Rain water can thus be said to act as a solvent on the rocks, though strictly speaking it first converts certain of their constituents from an insoluble to a soluble form and then dissolves them.

From a geological point of view, weathering is a very rapid process, but by the human time-scale it is slow. Since the most important processes involved are chemical, the rate depends largely on temperature. In a hot climate, like that of the lowlands of the Pacific islands, where the soil temperature is about 77° F. at a depth of a yard and varies very little, soil formation goes on very much faster than in a temperate climate such as that of Europe or of the high mountains of Hawaii and New Guinea.

Even after a soil has come into existence, weathering still continues. Like an organism the soil develops and we can speak of it as being young and immature, or old and mature. The measure of its age is, however, not its actual age in years, but the degree to which weathering has advanced, or the amount of weatherable material remaining in it. Two soils of the same actual age may be at very different stages of maturity. In islands such as Samoa, where there are lava flows of many different ages, there are excellent opportunities of comparing soils of different degrees of maturity derived from similar parent materials under similar climatic conditions.

Apart from temperature the climatic factors most influencing soil development are rainfall and evaporation, or rather, the ratio of rainfall to evaporation. When rainfall exceeds evaporation, as in the wet zones of the Pacific islands, and provided that the soil is sufficiently porous, the movement of water in the soil must be mainly downwards, the excess draining away to streams and rivers. The descending water current consists of rain water—that is, water with air, including carbon dioxide and nitrogen compounds, in solution. As the water passes down it takes up organic matter from the dead plants and animals at the surface, becomes richer in carbon dioxide, and dissolves small quantities of salts. This very dilute solution acts on the rock beneath. Thus in a wet climate there is a slow but unceasing trend towards soil impoverishment, which becomes much faster when the natural forest cover is removed to make way for cultivation. In Samoa the coconut and cocoa plantations, especially on the more mature soils, already show a slight but significant fall in productivity, which is probably largely due to loss of plant nutrients from the soil. The comparative fertility of the volcanic islands generally is due to the prevalence of young little-weathered soils.

The primary products of weathering are removed in order of their solubility. The bases begin to go first because they are the most soluble constituents ; they are washed from the upper into the lower layers of the soil and are eventually carried away with the drainage water, though for a while they may be retained by adsorption on humus or other colloidal substances such as clay particles ; the soil in consequence becomes more and more acid in reaction. Later the silica, alumina and iron oxides may follow suit, but the order in which they are removed depends largely on the amount of organic matter carried in the soil water. In water containing large amounts of organic matter, alumina and iron oxides are more soluble than

silica, thus silica remains behind and alumina and iron oxides are carried down into the deeper layers. Under these conditions the mature soil consists largely of silica and owing to the loss of iron oxides, to which most soils owe their colour, it often has a bleached or whitish appearance. In water containing little or no organic matter silica is more soluble than alumina and iron oxides. Silica is therefore carried down while, as the soil matures, it tends to consist more and more largely of alumina and iron oxides, the latter giving it a red, yellow or brown colour. The process by which alumina and iron oxides are removed preferentially, leaving silica behind, is called *podzolization*; the opposite process is *laterization*. The soils ultimately resulting from these processes are respectively called *podzols* and *laterites*. Laterites are bright red rock-like soils consisting of little more than alumina and iron oxides. They are highly infertile, but fortunately do not seem to be of common occurrence, at least in the Pacific islands. Generally the process of laterization stops short of true laterite and then the mature soil is termed *lateritic*. The progress of laterization can be measured by determining the ratio of silica to alumina and iron oxides in the clay fraction of the soil.

The amount of organic matter in the soil water, which thus has such an important effect on soil development, is mainly a function of temperature. In a well-aerated soil dead leaves and other organic remains are acted on by fungi and bacteria which gradually convert them to a mixture of substances, usually black or brown in colour, known as humus. In course of time the humus itself is attacked and converted mainly to carbon dioxide and water, any mineral matter in it being set free in the soil. The amount of humus in the soil depends on the balance between the rate of formation and the rate of breakdown of organic matter. The relative speed of the two processes depends on the temperature. Where it is high, as in tropical lowland soils, plant growth is rapid and dead plant remains are added to the soil in great quantities ; on the other hand, the high temperature also accelerates the action of micro-organisms so that the plant remains are broken down as fast as they are deposited. It is found that at a temperature of 77° F. or higher, under conditions of good aeration, the breakdown processes overtake the formation of organic matter ; in practice this does not mean that there is no humus at all, but the quantity is relatively small. Below 77° F. the rate of production of organic matter exceeds the rate of breakdown and humus tends to accumulate.

What has just been said is true only as long as the soil is well aerated. When it is badly aerated, that is to say, when there is a deficiency of oxygen, as when the soil is waterlogged, the activity of the micro-organisms is hindered and humus may accumulate even at temperatures over 77° F. This is especially liable to happen when the ground water is exceptionally poor in lime and other bases, as when it drains rocks init ally very poor in these substances. In the lowlands of New Guinea under such conditions humus may accumulate to such an extent that layers of peat are formed, sometimes many feet thick.

In the lowlands of the Pacific islands, then, except in certain types of swamp, the soil contains very little humus and the descending current of soil water will be deficient in organic matter. If this is so, s lica, as has been shown, will be removed preferentially to alumina and iron oxides; the dominant soil-forming process will be laterization. This is well shown in Samoa where the percentage of silica falls from over 20% in the younger soils to under 3% in the older. The lateritic soil formed under a high and well distributed rainfall is known as a tropical red earth. This is the characteristic soil type of most of the region of the earth in which the natural vegetation is tropical rain forest (p. 136). Where the rainfall is particularly heavy and there is practically no dry season, lateritic soils are found which are yellowish or brownish rather than red; these soils do not differ chemically from the tropical red earths, except in the higher degree of hydration of the iron oxides. In some places where the colour of the soil would be expected to be red it is masked by special constituents; thus in Oahu (Hawaiian islands) the soil is purplish owing to the abundance of manganese.

In the higher mountains of New Guinea and the Hawaiian islands, and doubtless on a smaller scale in the higher parts of the other 'high' islands, there are areas in which the mean annual temperature is less than 77° F., so that humus accumulation becomes possible and podzolization becomes the chief soil-forming process. Podzols, similar to those found in other cool moist climates, for instance in northern Europe, are found in the mountains of New Guinea—e.g., in the upper Ramu valley (approximately 9,000 ft.)—and similar soils probably occur in Hawaii. These soils are naturally acid and very poor in plant nutrients; this, in addition to their inaccessible situation, makes them unsuited for the cultivation of ordinary crops. Where there is a combination of low temperatures and bad drainage, as in the Alakai swamp on Kauai (5,000 ft.) and on other 'summit

bogs' of the Hawaiian islands, peat accumulates, as in some lowland swamps.

So far we have considered only those parts of the 'high' islands where there is a heavy rainfall, and where the yearly total greatly exceeds that lost by evaporation. In the dry zones of Fiji and the Hawaiian islands, and probably in New Caledonia and the dry areas of New Guinea, conditions are very different. There is a low rainfall, in some places well under 30 in. per year, and it is probable that for at least a large part of the year evaporation exceeds precipitation. This entirely alters the conditions for soil development, as there is no longer the continual downward stream of water in the soil and the tendency for soluble substances to be removed is much less. The resulting soil is red to brown in colour : it is much richer in bases than the wet zone soils and is therefore neutral or alkaline in reaction. The so-called 'reddish brown' and 'red desert' soils

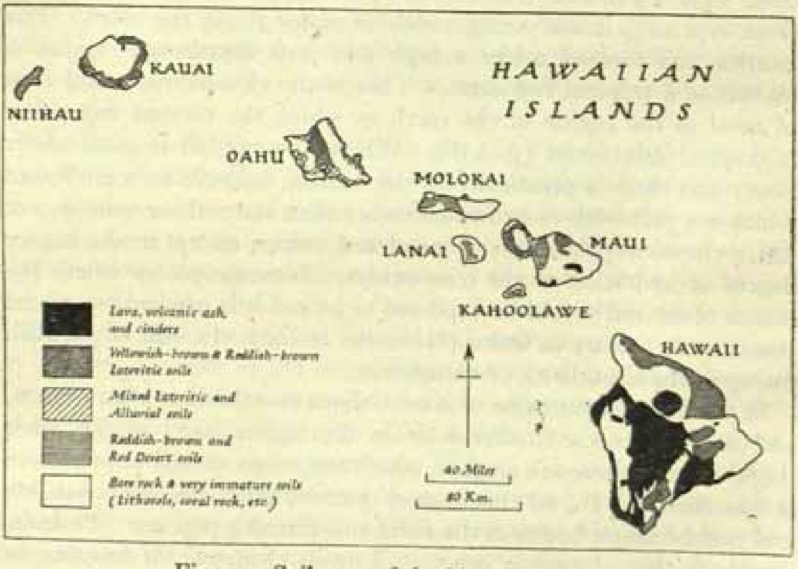

Fig. 51. Soil map of the Hawaiian islands
Based on *Soils and Men* (*Year Book of the U.S. Department of Agriculture*, 1938), *end paper* (Washington, 1938).

of the dry zones of the Hawaiian islands (Fig. 51) actually contain visible particles of calcium carbonate. The agricultural possibilities of such soils are usually limited by lack of water, but when irrigated they may prove fertile. Fig. 51 may be compared with land utiliza-

tion maps of individual islands (vol. II, Figs. 104–9), and the distribution of lateritic, mixed lateritic and alluvial soils, and reddish-brown and red desert soils, with the map of irrigated areas in the same group (vol. II, Fig. 103).

In the coral islands soil development has been little studied. Here the climate is in general drier than in the 'high' islands and

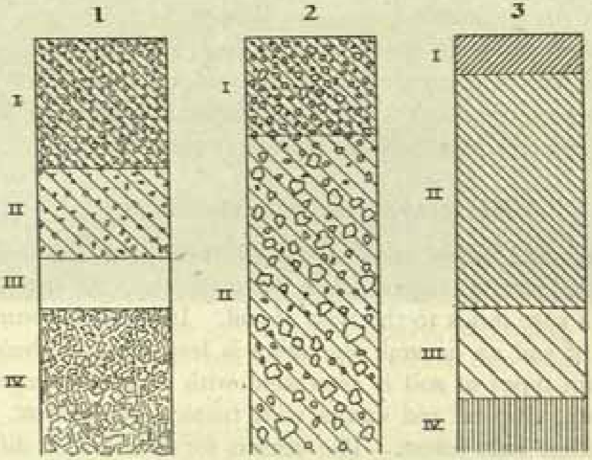

Fig. 52. Immature and mature soil profiles in the Pacific islands

1. Fanning island, central equatorial islands. An immature soil, formed under a moderately wet climate; parent material, coral limestone. I, 0–10 in., dark brown soil mostly composed of coral and shell fragments of average diameter 0.4–0.6 in.; II, 10–17 in., light brown soil mostly composed of coral fragments of average diameter 0.2 in.; III, 17–21 in., white hard pan of calcium carbonate of variable depth and thickness; IV, 21 in., white coral fragments.

2. Saleimoa, Western Samoa. An immature soil formed under a wet climate; parent material, volcanic rock (young lava flow). The soil is stony, but fairly deep and is agriculturally productive. I, 0 to 6–9 in., dark yellow-black-brown stony loam with good crumb structure; II, 9 in., dark red-brown-yellow, very free stony sandy loam. Soil reaction neutral at all levels.

3. Tiai, Western Samoa (altitude 2,250 ft.). A mature soil formed under an excessively wet climate; parent material, volcanic rock (old lava flow). A deep soil, but much less fertile than 2. I, 0–3 in., black-brown-yellow sticky clay loam, acid in reaction (pH 4.9); II, 3–21 in., dark brown-orange sticky clay loam; acid in reaction (pH 5.8); III, 21–27 in., compact dark yellow clay loam; IV, 27 in., reddish brown compact clay loam.

Profile 1 is after E. Christophersen, 'Vegetation of the Pacific Equatorial Islands', *Bernice P. Bishop Museum Bulletin*, no. 44, p. 39 (Honolulu, 1927); profiles 2 and 3 are from data of W. H. Hamilton and L. I. Grange, 'The Soils and Agriculture of Western Samoa', *New Zealand Journal of Science and Technology*, vol. XIX, pp. 593-624 (Wellington, 1938).

the parent material, coral rock, is peculiar, consisting of little else than carbonate of lime. Often there is little soil of any kind, what there is being sandy or gravelly in texture and full of limestone particles (Fig. 52). The tendency to loss of bases is less important here, but the thinness of the soil and its excessive porosity make it unfavourable for plant growth. On Manihiki (Cook islands) the inhabitants even find it worth while to import soil by schooner from Rarotonga for vegetable growing. Where the climate is wet and has had long enough to operate, as on Niue, an upraised coral island, a yellowish brown lateritic clay soil is developed, which though rarely more than 6 in. deep, is not essentially different from soils developed from other parent materials under similar climates.

Soils and Natural Vegetation

In England and many other parts of the world the correlation of soil and natural vegetation is so close that the vegetation is generally a sure index to the type of soil. In tropical countries the influence of soil on natural vegetation is less striking, though each of the main types of soil is associated with a type of vegetation—for instance, tropical red earths with tropical rain forest, podzols with montane rain forest. The reason for this is not difficult to understand ; the influence of the climate is so powerful that it tends to over-ride differences of soil due to different parent rocks. The importance of soil in determining the type of natural vegetation in the tropics, must not, however, be under-estimated. In the Pacific islands the correlation of soil and natural vegetation has been little studied, though the difference in vegetation between volcanic and limestone areas is obvious to anyone, especially in islands like some of the Fiji group where limestone and volcanic rocks are found side by side. Other examples of the influence of soil on vegetation will no doubt be shown by more detailed studies in the future.

Soils and Agriculture

When the natural vegetation is destroyed and replaced by an agricultural crop differences of soil which showed little effect on the natural vegetation may take on great importance. The appreciation of these soil differences and their effects may therefore decide the success or failure of the crop. To understand why this is so, it is necessary to consider the relation of vegetation to soil a little more closely.

Plate 32. Beach vegetation, Mangareva

This view shows the summit of the coral rubble dam formed from the eroded reef flat.

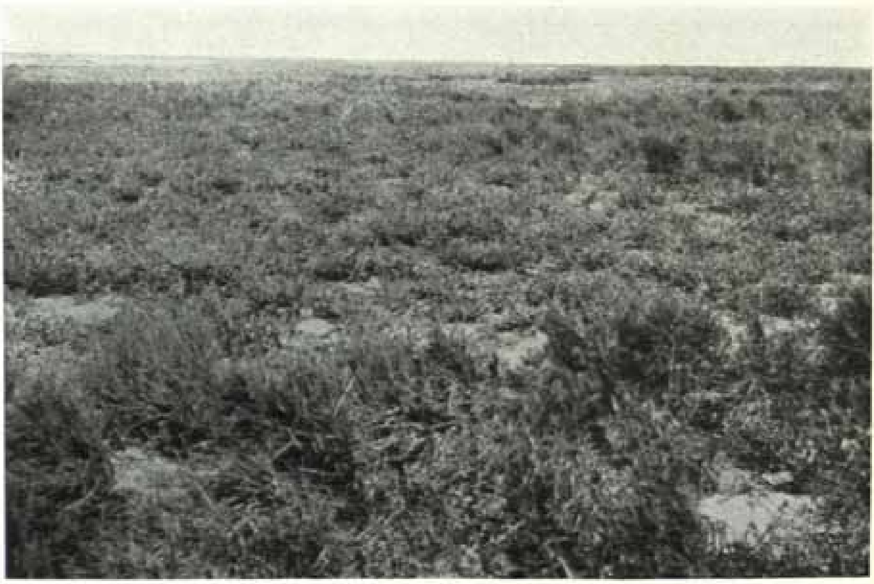

Plate 33. Vegetation of Baker island

This shows the typical vegetation of a coral island in the central equatorial area. The plants are *Lepturus repens* (a grass), *Boerhaavia tetrandra* and *Portulaca lutea*.

Plate 34. Undergrowth of tropical rain forest in the interior of Bougainville, Solomon islands
The palm in the centre is *Licuala polyschista*.

It is a remarkable fact, and one which is very disconcerting for the agriculturist, that a soil which under natural conditions bears a luxuriant rain forest, when cleared and cultivated may give good crops for only a very few years, or may prove a failure from the start. The explanation lies in the fact that the plant nutrients, such as salts containing calcium, phosphorus, potassium, etc., on which soil fertility largely depends, constantly circulate between the plants and the soil. These plant nutrients, as has already been shown, are among the most soluble products of weathering and therefore the most easily lost. In a damp climate the descending water currents in the soil continually tend to wash these soluble materials from the upper to the lower layers of the soil, where they may be out of reach of the plant roots. Eventually they are lost in the drainage water. Where there is a covering of natural vegetation, for instance a tropical rain forest, a large proportion of these nutrients are taken up by the plant roots immediately after they are set free by weathering. Part is also held by adsorption on the humus and colloidal clay particles. When the plants shed their leaves or die, their dead remains are converted to humus and the mineral nutrients are again set free in the soil. There they are immediately taken up again by plant roots or adsorbed by colloids. Thus after they are liberated from the rocks the mineral nutrient substances are always circulating from soil to plant and back again. Only a small amount is lost in the drainage water and this is made good by fresh supplies set free by weathering. There is thus a nearly perfect equilibrium between vegetation and soil, an illustration of the statement made earlier that plants and soil form parts of a single interconnected system.

When the forest is cleared to make way for cultivation this equilibrium is suddenly upset. The felled trees are either burnt or left to rot. Their remains are rapidly converted to humus by microorganisms and the humus itself is broken down to carbon dioxide and water. When the soil surface is exposed to the direct rays of the sun, its temperature rises and the breakdown of organic matter is so accelerated that the small amount of humus previously present in the soil soon disappears. The net result of all this destruction of organic matter is that most of the mineral matter which was safely locked up in living plant tissues and in the humus is suddenly set free. As one writer puts it: 'The entire mobile stocks of mineral nutrients are put into liquidation and, as is usual at a forced sale, they go at give-away prices and the advantage reaped is by no means commensurate with their value.' The sudden release of mineral

matter may mean that very good crops can be obtained for a few seasons, but as the minerals are gradually washed away by the rain and removed in the crops the soil becomes less and less fertile until it becomes unprofitable to cultivate.

It is easy to understand why the native agriculturist prefers the extremely destructive system of shifting cultivation in which only a very few crops are taken off the same piece of ground. Much European agriculture in the tropics has been little more permanent; the forest has been cleared, the mineral capital of the soil consumed in a very few years and then the land has been abandoned. Many agricultural areas in the Pacific islands, including large parts of Fiji, Samoa and Hawaii, appear to be able to maintain their fertility for long periods, apparently indefinitely. This fortunate state of affairs is due, as we have seen, to the presence of young soils still rich in weatherable materials from which calcium, potassium and other plant nutrients can still be released. In some plantations in Samoa, especially on the more mature soils, there has been already a slight but significant fall in productivity which is probably due to the loss of plant nutrients from the soil. This loss of nutrients goes hand in hand with laterization and it has been found that crop yields are in direct proportion to the percentage of silica in the soil.

The European agriculturist has the advantage over the native in that he understands the use of fertilizers and within limits can compensate the natural deficiencies of the soil. Soil research in the Pacific islands has been mainly concerned with detecting and measuring mineral deficiencies in agricultural soils in order to apply fertilizers in the most economical way. One of the most common needs of Pacific soils is lime, and liming, often given in the form of dressings of coral sand, is a standard method of treatment. Lime has a number of different effects on the soil; it releases potassium and other bases by the process of base exchange, it improves the texture of many soils and it neutralizes acidity. With lime, as with other fertilizers, the treatment has to be suited to the requirements of the particular crop. Most tropical crops grow better on neutral or slightly alkaline than on acid soils; the banana, for instance, becomes liable to Panama disease under acid conditions. Tea, however, likes an acid soil and is injured by liming. Even when the fertilizer requirements of a soil are known, problems may remain. For instance, Hawaiian soils have a remarkable power of fixing phosphate fertilizers, that is, they convert them into a form in which they are not readily available to plants.

Soil analysis sometimes reveals the presence in the soil of constituents poisonous to plants, the ill effects of which can be neutralized by suitable fertilizers. Thus on some very acid Hawaiian soils crops are sometimes injured by the toxic effects of iron and aluminium. The soils of Samoa contain abnormally large amounts of chromium which is known to be toxic to plants; it has however been shown that the chromium is in an 'unavailable' form and it is therefore unlikely that it causes any damage.

Soil Erosion

One of the chief problems of soil utilization is that of soil erosion. Under a covering of natural vegetation the soil is protected, but when the land is cultivated the surface is exposed to erosion by rain and wind. The finer particles of soil may be carried away so that the texture of the soil becomes more and more sandy, or the top soil may be removed bodily, together with its humus and other valuable constituents. In extreme cases the whole of the soil may disappear, leaving only the bare rock. Often the land becomes carved into deep gulleys down which floods pour during storms, spreading mud over roads and flat land. Though generally erosion is economically disastrous, it occasionally has compensating advantages. Thus on the Ewa sugar plantations, on Oahu, 200 acres of new and fertile cane land have been built up by leading flood water containing soil washed off the hills through specially constructed drains on to the coral plain; 3½ in. of new topsoil have been spread over 140 acres on which cane previously grew badly owing to the thinness of the soil.

In the Pacific islands, with their steep slopes and heavy rainfall (much of it in the form of torrential downpours), conditions might be expected to favour erosion, but for a number of reasons damage has not so far been as serious as in many other parts of the world, though in limited areas it has been catastrophic. In the Hawaiian islands there has been great damage in some places; on the island of Kahoolawe, for example, almost all the soil has been lost, mainly by wind erosion of soil exposed by overgrazing. In Fiji much erosion has taken place—in the Kaloba area of Viti Levu 2 ft. of soil have been lost in five years—but erosion is not as yet a major problem. Overgrazing has led to disastrous erosion in the Marquesas, notably on Eiao, where after heavy rain streams of muddy water pour into the sea, carrying away hundreds of tons of soil.

The speed and extent of erosion depend on many factors. Besides the slope and the quantity and character of the rainfall, the texture of the soil itself is important. Hawaiian soils are mostly so permeable that the rain quickly penetrates and there is little run off, hence there is much less erosion than might be expected. The underlying rock is also a factor; thus the soapstones of Fiji are slippery when wet, so there is a tendency for the whole mass of soil to slide off.

The nature of the soil covering is of great importance. Different crops and methods of cultivation make a great difference to the amount of erosion. In the sugar-cane fields of Hawaii, for instance, there is comparatively little erosion, because the cane plants tend to hold and protect the soil and because the soil is loosened only when it is deeply ploughed, once in 10 to 12 years. Pineapple cultivation, on the other hand, is more harmful. The cover is less good and it is a common practice to plough the land in straight lines which may run perpendicular to the contours, so that the furrows form channels for flood water; also the land is cultivated in three-year cycles, with fallow periods of 6 to 9 months between, during which erosion has free play. Grassland is subject to erosion only if it is too heavily grazed and the grass covering wears thin. In many of the Pacific islands erosion has resulted from overgrazing by domesticated animals such as sheep and pigs which have run wild.

Though soil erosion has not yet become an urgent problem in most Pacific islands, it is likely to become so very soon, as the amount of agricultural land is not large in relation to the needs of the population. Only in the Hawaiian islands have energetic steps been taken to check erosion. Among the more important measures that can be adopted are changing from straight-line ploughing to ploughing along the contours, using a rotation of crops so as to eliminate a fallow period, and reducing the overstocking of pastures, so that each area of grassland can be 'rested' in turn. Where the covering of plants has been destroyed a new cover can be provided: in Hawaii the introduced *algaroba* tree (*Prosopis*) and certain grasses have been very useful for colonizing badly eroded land. Where gully erosion has taken place channels for controlling the run-off must be made, check-dams constructed and trees planted on denuded areas.

Erosion control involves difficult problems of administration and agricultural education. It is greatly affected by the system of land tenure. Where the land is cultivated by a tenant who can easily

move to fresh ground when the productivity of the soil is exhausted there is no incentive to troublesome measures of soil conservation. In Hawaii, when public land is leased to stockmen, it is now customary to insert a clause in the lease requiring the tenant to remedy and prevent soil erosion.

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A Handbook on Hawaiian Soils by W. W. G. Moir and others (Association of Hawaiian Sugar Technologists, Honolulu, 1935) is a comprehensive account of the soils of the Hawaiian islands, mainly in relation to sugar-cane cultivation; it has a full list of literature up to the date of publication. In addition mention should be made of E. C. J. Mohr, 'Tropical Soil Forming Processes and the Development of Tropical Soils, with special reference to Java and Sumatra' (mimeographed translation by R. L. Pendleton), *College of Agriculture, University of the Philippines, Experiment Station Contribution*, no. 655 (Manila, 1930), much of which is applicable to the soils of the Pacific islands.

Chapter V

VEGETATION

General Features : Types of Vegetation : Coastal Vegetation : Vegetation of Coral Islands : Vegetation of 'High' Islands : History of the Vegetation : Notes on Some Common Plants : Bibliographical Note

The islands of the Pacific enjoy a tropical, or at least a sub-tropical, climate and for the most part have the perennially green, almost overpoweringly luxuriant vegetation characteristic of the wet tropics. The leeward Hawaiian islands in the north, Juan Fernández, Easter island, the Kermadec islands, etc., in the south, lie, it is true, well outside the two tropics, but their climate is so nearly tropical that their vegetation is not fundamentally different from that of the islands nearer the equator.

GENERAL FEATURES

So far as plants are concerned, the chief features of a tropical climate are a constantly high temperature, with little seasonal change, combined with abundant rainfall well spread through the year. Under such conditions plants can grow and reproduce at all seasons, and where the natural vegetation has not been modified by man and his domestic animals, forests of evergreen trees are the rule. In some parts of the Pacific, e.g., the drier parts of New Guinea and Easter island, the present-day vegetation is not evergreen forest, but grassland or savannah ; it is probable, however, that here too there was forest in the not very distant past. In the serpentine region in New Caledonia there is much low scrub in which trees apparently cannot grow ; this seems to depend on a combination of a porous soil with a comparatively dry climate. Nowhere in the Pacific islands are there deciduous forests shedding their leaves regularly in the dry season like the teak forests of Burma and the south-eastern Malay archipelago.

Though the vegetation of the Pacific looks much the same at one time of year as another, many of the plants show slight seasonal changes. In Samoa, for instance, where there is a difference of only a little more than 2° F. between the mean temperature of the hottest and the coldest month, many of the trees have definite flowering seasons. In the New Hebrides and Tikopia, the flowering of

Plate 35. Tropical rain forest, Gazelle peninsula, New Britain
The large trunk in the centre is *Eucalyptus deglupta*, a giant gum tree which forms the top storey of the forest in this area.

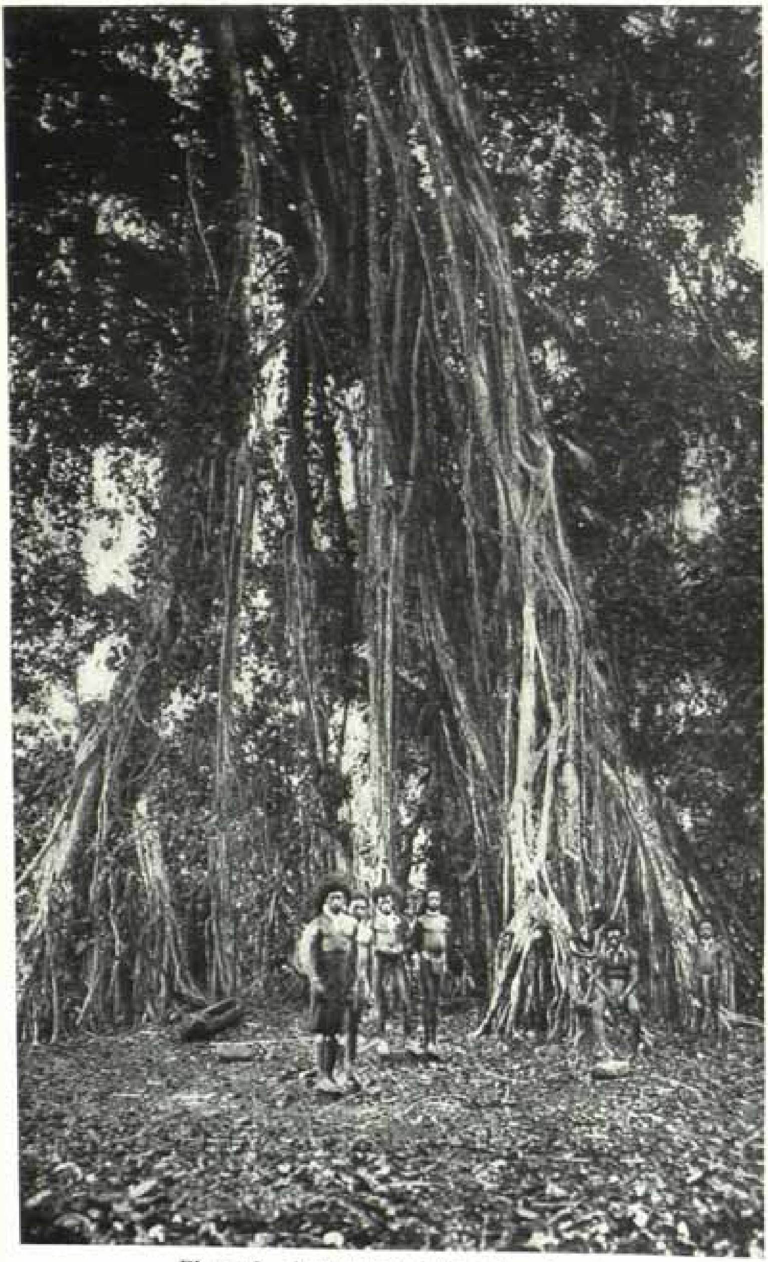

Plate 36. Banyan fig (*Ficus chrysolaena*)
This specimen is from Ragetta island, near Madang, New Guinea.

Erythrina indica tells the natives when to plant their yams. Though there are no deciduous forests, many individual species of trees shed their leaves at regular or irregular intervals.

Apart from the tropical climate the chief factor in the Pacific which has influenced the vegetation is the fact that the land area is composed of a large number of widely separated islands, varying in size from almost continental New Guinea to tiny reefs and atolls on which a handful of plants maintain a precarious foothold. Since for most plants it is much more difficult to spread across wide stretches of sea than across the land, the isolation of the Pacific islands has had important consequences for their plant life. In the first place, though it would be difficult to give even an approximate estimate of the number of plant species in the Pacific islands, there is no doubt that, if the great island of New Guinea is excluded, the total flora is poor compared with that of the other great tropical regions. The flora of individual islands or groups is not large even by European standards; compared with similar areas in Malaya or tropical America it is extremely small. Thus New Caledonia has about 2,300 species of flowering plants and the Hawaiian islands about 850, compared with some 1,500 in the British Isles and over 10,000 in Borneo.

A second consequence of isolation is the large number of endemic species, that is, species found only on a single island or group of islands, as for instance the palm *Juania australis* found only on Más-á-tierra (Juan Fernández) and the remarkable tree *Fitchia* which is found nowhere in the world except in Rarotonga and the Society islands. Some endemics are believed to be newly evolved species which have not yet had time to spread, others are probably very old species which have died out everywhere but where they are now found. A high percentage of endemic plants and animals is characteristic of remote islands and isolated mountain tops. In New Caledonia about 77% of the flora is endemic, in the Hawaiian islands about 70%, though in most of the high islands the proportion of endemics is not as high.

The Pacific islands are so varied in character and are spread over so large a part of the earth's surface that their vegetation would also be expected to be extremely varied. On the whole, however, the differences in the vegetation between one part of the same island and another are often more striking, at least to the non-botanist, than those between very widely separated islands. For example, nothing could look more different than the sun-baked grasslands

on the leeward side of Viti Levu in Fiji and the permanently moist evergreen forest on the windward side. On the other hand the vegetation of two atolls thousands of miles apart may be extremely similar, and the rain forest of Juan Fernández is not very different at first sight from that in the Kermadecs, some 6,000 miles away. In general, as in the examples just given, differences or resemblances in vegetation depend on difference or similarity in total rainfall, though in New Guinea and Hawaii where there are mountains reaching the region of perpetual snow, or very nearly so, there are striking altitudinal differences in vegetation depending on temperature as well as rainfall.

In all the inhabited islands, in addition to the native plants, there are introduced species brought in by Europeans or by the native inhabitants. Some of these introduced species are cultivated plants, many of which have run wild and maintain themselves unassisted; others are weeds introduced unintentionally. The introduced flora has often proved aggressive and ousted the native flora over large tracts of country. Thus at low altitudes in the dry zone of Oahu in the Hawaiian islands the introduced plants have almost completely exterminated the native flora, and in many Pacific islands the visitor could spend a long time without seeing a single truly native plant. Usually, but by no means always, the native and the introduced floras do not mix, but occupy separate areas.

Broadly speaking the native flora of the Pacific islands (except that of groups like Juan Fernández and the Galápagos, which lie close to the coast of America) consists mainly of species which are either identical with species of the Indo-Malayan region (south-eastern Asia and the Malay archipelago), or are closely related to such species. There is thus good reason for believing that the majority of Pacific island plants or their immediate ancestors immigrated at some period from the west.

Though the flora of the Pacific has mostly come, recently or in the very distant past, from elsewhere, it is not without its peculiar forms of plant life, some of which are as remarkable as those found in any region of the earth and are very different from anything known elsewhere. The first place among these must certainly be given to the grotesque tree *Lobelioideae*, most of which are confined to the Hawaiian islands. These plants are related to the small blue *Lobelia* of English flower beds, but here they are trees, in some species 35 ft. or more high. The long narrow leaves are usually borne in a tuft at the tip of the otherwise bare branches, together

with the showy blue, purple or whitish flowers. Mention should also be made of the araucarias (related to the Chilean monkey-puzzle of English gardens), and other peculiar conifers of New Caledonia and New Guinea. One of these, *A. columnaris* (*A. Cookii*) gave its name to the Isle of Pines, and the appearance of the tall unbranched trunks is so odd that when the botanist Forster saw them from his ship on Cook's famous voyage he mistook them for basalt columns (Plate 48).

As well as these plants, which are not native outside the Pacific, there are some other remarkable-looking plants which the Pacific shares with other parts of the tropics. There are, for instance, a wealth of tree ferns and palms, the screw pines (*Pandanus*) with their queer twisted appearance and cone of prop roots (Plate 52), and the banyan figs, vast trees with a wide-spreading crown supported on a mass of descending aerial roots (Plate 36). In New Guinea, the Carolines and New Caledonia are found the curious and beautiful insect-eating pitcher plants, *Nepenthes*. *Myrmecodia*, an extraordinary plant with a swollen stem inhabited by ants, is common in the mountains of New Guinea (Plate 47).

Some Pacific plants, but not many, have been introduced into cultivation and carried to distant parts of the world. One example is the palm *Howea Belmoreana* which ornaments nearly every cinema and hotel lounge in Europe and North America; it is an endemic, native only in Lord Howe island, where collecting the seeds is the staple industry of the inhabitants. Another is the graceful Norfolk island pine, *Araucaria excelsa* (Plate 53), young plants of which are one of the commonest window decorations in English houses.

TYPES OF VEGETATION

In considering the types of vegetation in the Pacific islands a sharp distinction must be made between the 'low' islands—atolls and reefs of coral raised only a few feet above sea-level—and the 'high' islands, which are volcanic and frequently reach a height of 3,000 ft. (or much more). The 'low' islands are poor in species, very uniform in flora, and the vegetation consists largely of maritime and drought-resistant plants. The 'high' islands—and with them may be grouped New Guinea and other large islands of the Western Pacific—have a far richer and more varied vegetation. The coral islands are so small and so little raised above the sea that practically

all their vegetation is affected to some extent by salt water; it is thus hardly surprising that the plants which grow on them are mostly the same as those found round the shores of the 'high' islands. After dealing with the coastal vegetation of the Pacific in general, it will therefore be convenient to pass next to the vegetation of the coral islands.

Coastal Vegetation

On reefs and rocks between the tidemarks and for some depth below the low tide mark there is a rich flora of green, brown and red seaweeds. Most of the species and many of the genera are different from those familiar in England; for instance, the wracks (*Fucus* and related genera) which bulk so largely in the vegetation of our own shores are not found, the commonest large brown seaweeds being the Sargasso weed (*Sargassum*) and the related *Turbinaria*. Many of the Pacific seaweeds, especially those belonging to the group of red algae, deposit calcium carbonate, and along with the corals play an important part in reef building. In Hawaii seaweeds are of some economic importance as they are much valued by the inhabitants as food, some 75 different kinds of seaweed (*limu*) being used. The ancient Hawaiian nobility, like the modern Japanese, deliberately cultivated these plants, setting aside near their dwellings fishponds or sections of the coast to which desirable kinds of seaweed were transplanted, the unwanted kinds being weeded out.

The nature of the land vegetation of the coast depends mainly on whether the shore is sandy, muddy or rocky, as well as on the exposure to wave action. On sandy shores low-growing herbs, grasses and bushes are found (Plate 32), similar to the *strand vegetation* of Europe. It consists of a limited number of species most of which are rarely seen inland. Some of the commonest are the goat's-foot convolvulus (*Ipomoea pes-caprae*), species of *Vigna* and *Canavalia* (belonging to the pea family), *Lepturus repens* and other grasses. Except for the grasses most of these plants have a trailing or creeping growth and many have fleshy or hairy leaves. Unlike most land plants they are not killed by occasional flooding with salt water. Scattered among these low-growing plants or sometimes forming thickets or a definite belt on the landward side are found bushes a yard or more in height such as *Desmodium umbellatum*, *Pemphis acidula* and *Scaevola frutescens* (Fig. 53). In this scrub there may be occasional trees of coconut (Plate 31), the tree heliotrope,

(*Tournefortia*, Fig. 54), *Hernandia ovigera*, etc. On reefs and rocky shores there are generally scattered bushes extending as far from the shore as the influence of the spray is strongly felt, and consisting

Fig. 53. *Scaevola frutescens*, sea-lettuce tree

A tree or shrub common on the coasts of most Pacific islands. The leaves are a fresh green colour and the flowers are almost white. Drawn from *Botanical Magazine*, vol. LII, plate 2732 (London, 1827).

almost entirely of species such as *Scaevola frutescens*, *Pandanus*, etc., which are also found on sandy shores.

Where the sandy beach is wide and the natural vegetation has not been destroyed, a strip of forest of very characteristic composition may develop on the landward side ; this is the *beach forest*. Like the strand vegetation it is formed chiefly of species not found inland. At its best the beach forest is a narrow belt of trees 100 ft. high or more, but often it is much lower and does not form a continuous belt. Good beach forest is only seen on the less thickly populated islands, because elsewhere it is generally destroyed or reduced to a

mere vestige to make room for plantations of coconut palms. In the Solomon islands the natives like to leave the beach forest to screen their villages from unwelcome visitors coming by sea. Common trees of the beach forest are *Barringtonia asiatica* (Fig. 55),

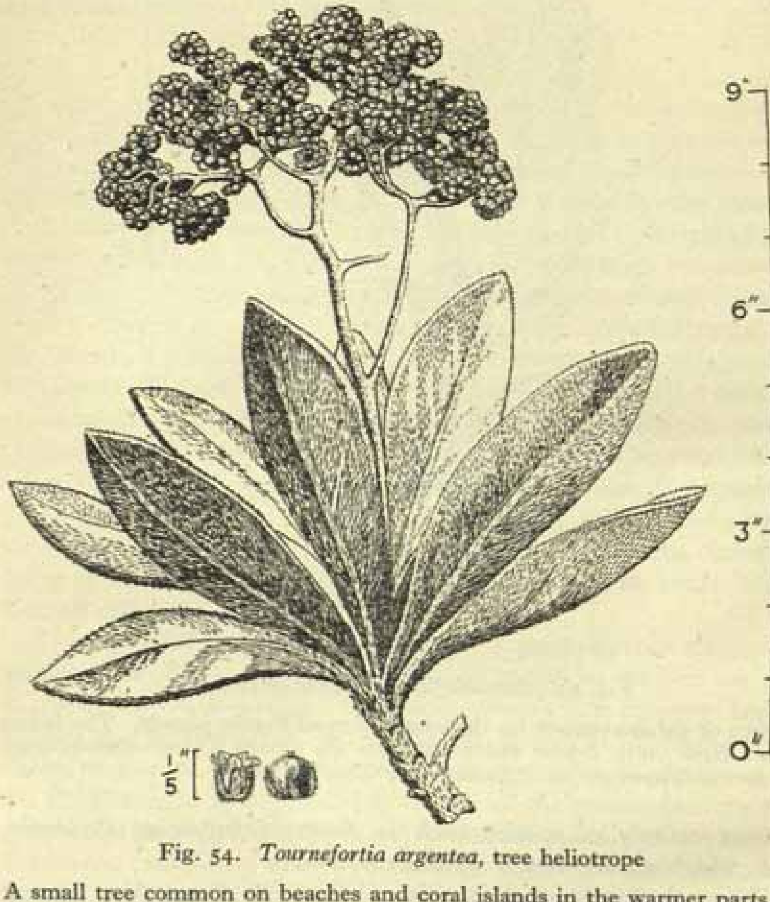

Fig. 54. *Tournefortia argentea*, tree heliotrope

A small tree common on beaches and coral islands in the warmer parts of the Pacific. The flowers are purple and the leaves conspicuous for their covering of silvery hairs. Drawn from W. E. Safford, 'The Useful Plants of Guam', *Contributions from the United States National Herbarium*, vol. IX, plate 68 (Washington, 1905).

Calophyllum inophyllum (Fig. 56, Plate 30), *Cordia subcordata*, *Hibiscus tiliaceus* (Fig. 67), *Terminalia catappa* (Fig. 57), *Thespesia populnea* and *Cerbera* species. In the Western Pacific (in New

Guinea especially near river mouths) the graceful *Casuarina equisetifolia* (Fig. 66) often forms large stands unmixed with other trees. The outer edge of the beach forest is often fringed with

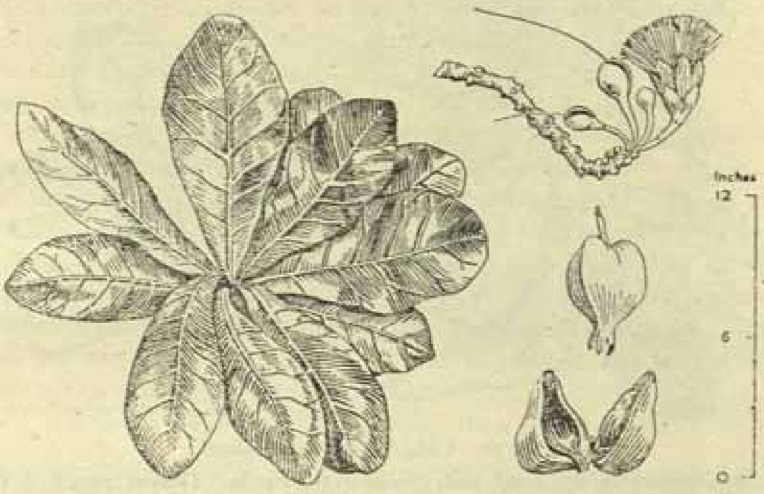

Fig. 55. *Barringtonia asiatica*

A large tree characteristic of the beach forest in the Pacific islands. The four-angled fruits are one of the most common objects in the drift. Drawn from E. J. H. Corner, *Wayside Trees of Malaya*, vol. II, plate 72 (Singapore, 1940).

Pandanus tectorius or other species of *Pandanus*. With the trees are associated shrubs, woody climbers, and herbaceous plants growing both on the ground and as epiphytes on the trunks and branches. The leafless parasite *Cassytha*, looking like a tangle of orange string, often grows over the trees and bushes in masses.

In sheltered bays, lagoons and estuaries, usually on a muddy substratum, is found the mangrove, a peculiar type of low forest or scrub flooded by the tides. These mangroves cover vast areas on the south coast of New Guinea and are also extensively developed in Fiji, New Caledonia and other islands of the Western Pacific. East of Tonga and Samoa they are not met with again till the Galápagos and the west coast of South America (Fig. 58).

Mangroves grow where the land is rising, sometimes as fast as an inch a year, by the deposition of silt. As new land is built up and consolidated, so the mangroves push out further and further into the water. By obstructing the tidal currents the mangroves speed

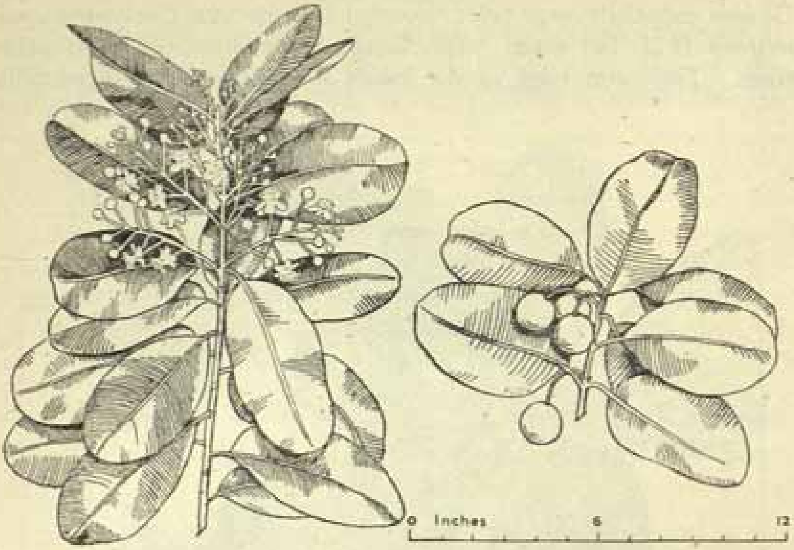

Fig. 56. *Calophyllum inophyllum*

A large tree of the sea coast, widespread in the Pacific. Drawn from E. J. H. Corner, *Wayside Trees of Malaya*, vol. II, plate 65 (Singapore, 1940).

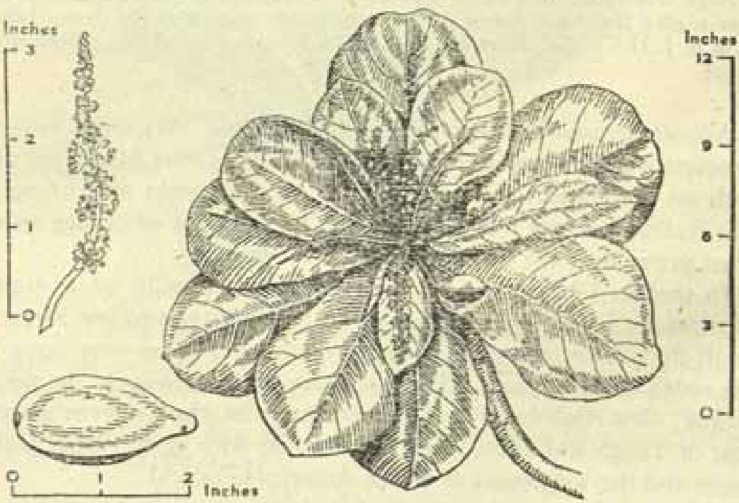

Fig. 57. *Terminalia catappa*, Indian almond, native almond

A common tree of the beach forest, also planted inland as a shade tree. Based on *Botanical Magazine*, vol. LVII, plate 3004 (London, 1830); and E. J. H. Corner, *Wayside Trees of Malaya*, vol. II, plate 45 (Singapore, 1940).

up the deposition of silt and thus play an active part in reclaiming land from the sea. They are of great economic importance for other reasons also; they provide excellent firewood and in Suva (Fiji) the whole supply of firewood for domestic and industrial use comes from the mangroves of the Rewa delta. The wood is hard and durable and is used for house building and many other purposes. The bark of mangroves is valuable for tanning, but little use has been made of it so far in the Pacific.

The mangroves are a group of trees not nearly related to each other botanically, but having certain remarkable features of structure and life-history in common, as well as the ability to grow on unstable mud periodically washed by the tide. The mangrove swamps of the Pacific are by no means so rich in species as, for instance, those of the Malay archipelago, but in addition to several species of mangrove trees, there are various shrubs, climbers, reeds and herbaceous plants, including the fern *Acrostichum aureum*. The mangroves themselves are evergreen trees varying from 10 to over 100 ft. in height. Most of them have shiny, leathery leaves

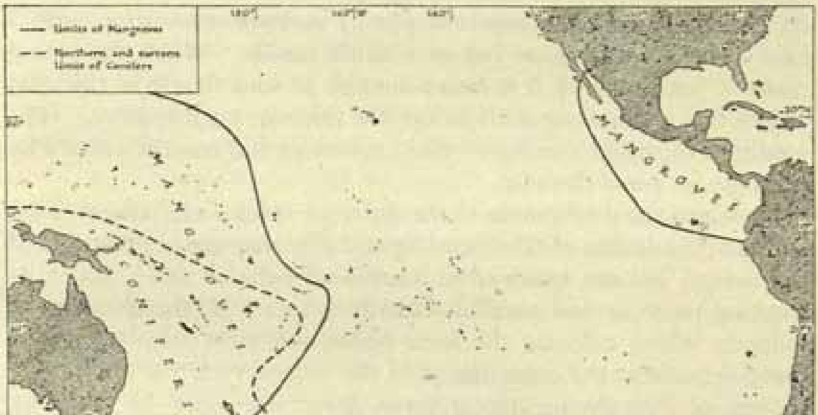

Fig. 58. Distribution of mangroves and conifers in the Pacific

All members of the mangrove group have been included. The eastern species (with one exception) are all different from those in the west of the area. Based on various sources.

and inconspicuous flowers, but the most striking features are their buttressed trunks and peculiar roots. In *Rhizophora* the trunk is supported on a mass of curved aerial roots (Plate 51), like very

slender flying buttresses. In *Avicennia* and *Sonneratia* the main lateral roots are horizontal and produce large numbers of small branches which grow vertically upwards through the mud and project several inches above the surface. These branch roots look like cigars or sticks of asparagus and beneath a large tree they are so numerous that one can hardly put one's foot between them. In *Bruguiera* the large lateral roots make a succession of upward bends or loops above the mud and are known as knee roots. The mud on which mangroves grow is almost completely deficient in oxygen and as the aerial roots of *Avicennia*, *Sonneratia* and *Bruguiera* are provided with very numerous lenticels (breathing pores), their main function was supposed until recently to be to act as aerating organs for the root system. Though they probably do this to some extent, they seem to have equal or greater importance in providing a means by which fresh rootlets can be given off at higher and higher levels as the mud accumulates. The dense growth of the aerial roots, and the softness of the mud make mangrove swamps unpleasant, but by no means impossible, to traverse.

A remarkable feature of many mangroves is that the seeds germinate before leaving the parent plant ; in some they grow into a heavy fleshy seedling, as big as a small candle. When the young plant at last drops off it is heavy enough to stick firmly in the mud at low tide and anchor itself before the tide can wash it away. The seedlings of mangroves float well in sea water and may be carried by currents for some distance.

Owing to the preferences of the different species of mangroves for different conditions of tidal flooding and soil, they are not distributed at random, but are arranged in a series of belts or zones, generally running more or less parallel with the shore. In the Pacific, the pioneers which colonize the least stable and most frequently submerged muds at the outer fringe of the mangrove forest are usually species of *Rhizophora*, but at times their place may be taken by *Avicennia* or *Sonneratia*. Other mangroves, such as *Bruguiera*, requiring less frequent submergence and different soil conditions, follow when the ground has been prepared for them by the pioneers ; the zonation thus represents an actual plant succession in which one group of species is superseded by another. As the pioneers are succeeded by more exacting species new land is added at the seaward edge and so the mangrove forest extends slowly out to sea. At the same time the soil level on the landward side rises and as the effect of the tides is felt less and less, the mangrove swamp with

salt ground water gradually turns into a freshwater swamp forest inhabited by quite different trees.

Associated with the mangrove swamp in the Western Pacific is a very characteristic community dominated by *Nipa fruticans*, a palm with a very short stem and feathery leaves, 20 ft. long or more. *Nipa* swamps form a very dark green belt contrasting with the lighter green of the mangroves along the sides of estuaries; they are particularly extensive along the gulf of Papua in New Guinea. *Nipa* likes brackish, not salt, conditions and unlike the mangroves it is not confined to places where silt is being deposited.

One of the most interesting facts about the coastal vegetation of the Pacific is its great uniformity throughout the whole area. Nearly all the component species have an extremely wide distribution and very few are endemics limited to small areas. The strand flora of one island is thus very like that of another, though thousands of miles away. The same is true to a large extent of the beach forest, and the reason is probably that coastal plants, unlike most inland plants, have seeds or fruits specially adapted to float in sea water by means of air cavities or spongy air-containing tissues (Fig. 59). They may thus be carried enormous distances by ocean currents and, if the conditions are suitable, may germinate when they are cast up. The mangroves differ somewhat from the other coastal plants in that all the species, though not the genera, found on the American shores of the Pacific, including the Galápagos islands, are different from those in the Western Pacific. (The one exception is an American species of *Rhizophora* found together with the Western Pacific species in Fiji and Tonga.) This difference between the Eastern and Western Pacific mangrove floras may be due to the seedlings of mangroves not being so well fitted for long sea journeys as are more resistant seeds and fruits.

The coastal vegetation of the Hawaiian islands is exceptional in lacking many of the widespread species and in having a number of endemic species not found elsewhere. This is doubtless owing to the extreme isolation of these islands (they are distant some 2,000 miles from the nearest continent or 'high' island) and because they lie off the track of the main ocean currents.

Vegetation of Coral Islands

Writers of fiction are apt to represent coral islands as having a luxuriant vegetation, abounding in useful and beautiful plants. This impression is very far from the truth; a typical coral island or atoll

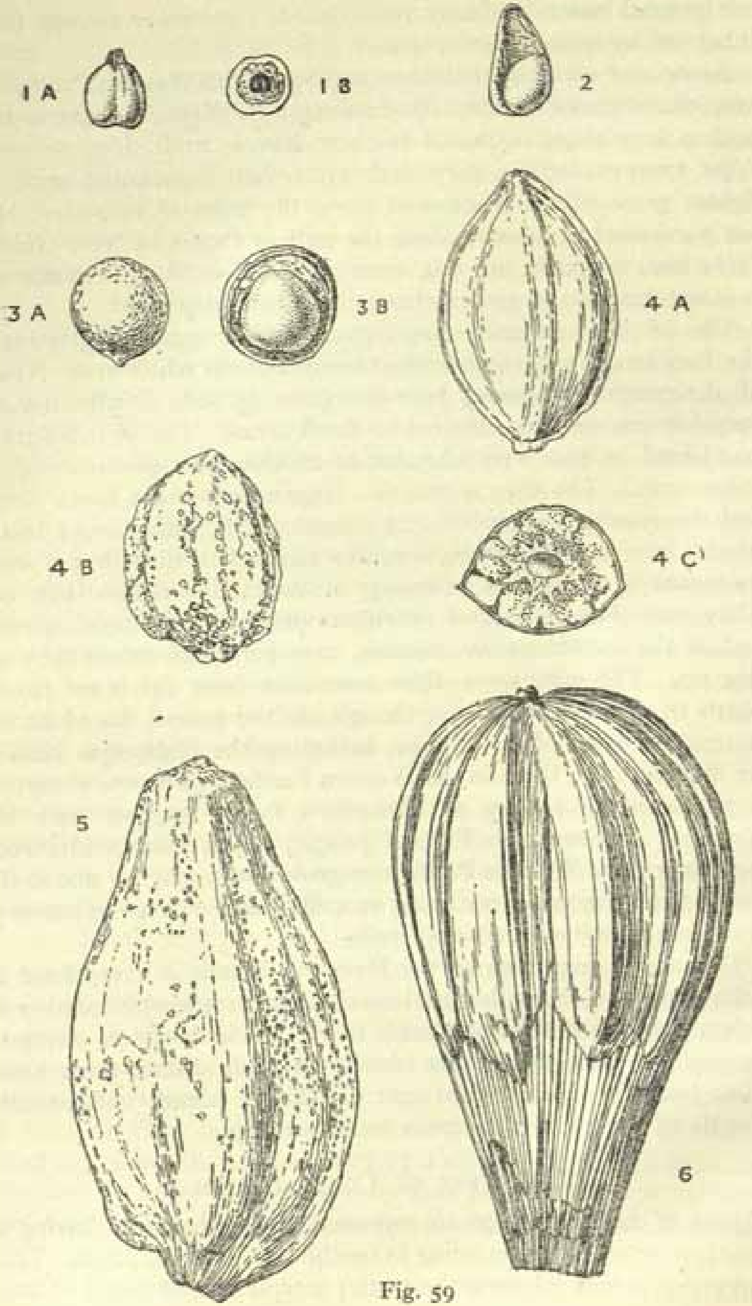

Fig. 59

has generally a poor and scanty vegetation of very few species (Plate 33). Besides the coconut palm and plants cultivated by the natives, there is often little but tufts of grass, scattered bushes and herbaceous plants. Many of the smaller islands are entirely treeless and even the larger and more fertile ones have little to show beyond woods composed of one or two kinds of trees. As far as useful plants are concerned, it is probably true to say that every food plant except the screw pine (*Pandanus*) has been introduced by man; no coral island would be habitable without the coconut, which though apparently self-supporting on some islands, was probably almost always planted in the first place.

The lack of luxuriance in the vegetation depends on the conditions for plant growth, which in the majority of coral islands suit only plants tolerant of severe droughts. (For the climate of the coral islands, see Chapter III). The effects of a low and unreliable rainfall are increased by strong evaporation and a porous soil with little power of retaining water. Besides the shortage of water, in many small coral islands the poverty of the vegetation is partly due to accumulations of phosphate which, though used as a fertilizer, is harmful to plants in large amounts.

Apart from cultivated plants, there may be as few as half a dozen species on a small island and under 50 on a large one. In a botanical survey of the central equatorial islands, comprising Christmas, Jarvis, Fanning, Washington, Palmyra, Howland and Baker islands, some 60 native flowering plants and ferns were found, in addition to about 20 introduced weeds, and a number of cultivated plants, most of which could not maintain themselves for long without human help. The flora of coral islands consists of a selection, varying slightly with each individual island, from a very limited

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Fig. 59. Pacific fruits distributed by the sea, showing means of flotation 1, *Scaevo'a frutescens*: A, whole fruit; B, cross-section, showing the two seeds (heavy black outline) enclosed in a corky flotation tissue (stippled), and the juicy outer layer. 2, *Morinda citrifolia*: stone of fruit with swim-bladder. 3, *Calophyllum inophyllum*: A, whole fruit; B, cross-section, showing seed surrounded by spongy flotation tissue. 4, *Terminalia catappa*: A, whole stone of fruit; B, stone worn by the sea, showing flotation tissue; C, cross-section of stone, showing numerous small cavities in flotation tissue (the seed has dropped out). 5, *Barringtonia excelsa*: fruit. 6, *Nipa fruticans*: fruit with the outer covering partly worn away and showing the fibrous flotation layer. The scale of 1 to 5 is about natural size. Based on A. F. W. Schimper, 'Die indo-malayische Strandflora', *Botanische Mitteilungen aus den Tropen*, Heft III, Tafel 7 (Jena, 1891).

repertory of species which extend with monotonous regularity over the whole Pacific. Though most of the coral island plants are very widely distributed, there are a few exceptions; for instance in Laysan, a coral island of the Hawaiian group, there is an endemic species of sandalwood. As with coastal vegetation in general, the explanation of the wide distribution of the coral island flora lies in its means of dispersal; nearly all the flowering plants have seeds or fruits which are either adapted to distribution by ocean currents or else are dispersed by birds. The few ferns and other lower plants reproduce by microscopic spores which are light and easily carried by the wind.

Even in the smallest islands the vegetation is not uniform, as slight differences of height, slope and soil produce a number of distinct habitats for plants, each of which has a slightly different assemblage of species. (Profiles showing types of vegetation for Jarvis and Sydney islands will be found in vol. II, p. 454.) The vegetation of the beach is on the whole like the strand vegetation already described, consisting of low-growing, salt-tolerant plants such as the goat's-foot convolvulus. The beach flora of the coral islands is however poorer than that of the 'high' islands and there are perhaps fewer plants of trailing growth. On many of the smaller and drier islands similar vegetation extends over the greater part of the area, most of the surface being occupied by scattered clumps of herbaceous plants such as *Sesuvium*, *Heliotropium anomalum*, *Portulaca* and *Boerhaavia*. The bunch grass *Lepturus repens* is very common, either by itself or mixed with the plants just mentioned; it is particularly characteristic of the beach crest and other open unprotected places (Plate 33).

In most coral islands at least a part of the interior is occupied by bushes, growing either scattered or as a thick scrub a yard or more high. The commonest species are *Scaevola frutescens*, *Sida fallax* and *Suriana maritima*. In some of the leeward Hawaiian islands the endemic *Chenopodium sandwicheum* plays an important part.

On the wetter islands forest covers most of the area and on many of the drier ones there are open woodlands or at least clumps of trees. The coconut is of course by far the commonest and most important tree. It is planted on every available acre of dry land, and even shingle banks and tiny islets with no other plants but a few lichens often have their few stunted and battered palms. Usually coconuts grow in plantations which are clearly of recent origin, but on

some islands there are forests of coconuts which look natural. Though the palms seed themselves, there is little doubt that these forests have all originated from trees planted by early Polynesian colonists. Other trees which form woods on coral islands are the tree heliotrope (*Tournefortia argentea*), which has a preference for the dry beach crest, and *Pisonia grandis*, which on some islands forms forests of considerable height and extent. Trees found in smaller numbers include the common beach-forest species such as *Calophyllum* and *Barringtonia*, also *Guettarda speciosa*, *Thespesia*, and *Cordia subcordata*; *Pandanus* species are common either in groups or scattered among other trees.

In some islands there is a damp central depression in which marsh plants such as the shrub *Jussieua erecta* are found. Washington island seems to be unique among coral islands in having two peat bogs covered with reeds, *Pandanus tectorius*, and the taro-like *Cytosperma chamissonis* as well as a freshwater lake in its low-lying interior. In the atolls of the Western Pacific poorly developed growths of mangroves (mainly *Rhizophora*) often fringe the central lagoon.

Under perfectly natural conditions it would be expected by analogy with other parts of the world that the vegetation of a coral island would undergo a natural development or plant succession. The island would first of all be colonized by a small number of low-growing and very hardy species, which would later give place to taller and more exacting species able to grow only with the help of the shelter and humus provided by the pioneer species. On islands with a climate damp enough for trees the succession would then lead to the establishment of forest; where the climate is drier the final stage would be some form of scrub. It is thus likely that the open vegetation of herbaceous plants and grasses, the scrub of bushes, and the woods of *Tournefortia*, *Pisonia*, etc., in this order, do in fact represent stages in a succession. But the course of development has been very much altered by human interference. Coconut palms and other trees have been planted and the demand for timber and firewood has checked the development of natural forests, or destroyed those already existing. On many islands phosphate digging has destroyed the vegetation over large areas; when the diggings are abandoned plants soon begin to colonize the bare ground and a new succession begins. On Nauru the fig *Ficus prolixa* has been noted as an early colonizer of worked-out phosphate lands.

VEGETATION OF 'HIGH' ISLANDS

The types of vegetation to be considered under this heading are so many and vary so greatly from island to island that it will be possible to survey them only briefly. For the purposes of description a rough division may be made into vegetation of wet and dry climates and into primary and secondary types.

It has just been pointed out that the vegetation of coral islands tends to undergo a natural development or plant succession; the same is of course true of all other vegetation. Plant successions consist of a series of unstable stages, each one preparing the way for the next, till a final relatively stable stage is reached called the climatic climax, because the climate sets a limit to further development. Throughout the Pacific area, except for a few small regions where the conditions seem to be too dry for any sort of tree growth, the climax vegetation is evergreen forest. Where the climate is dry or semi-dry, the climax will be dry evergreen forest, scrub savannah or grassland. Occasionally the soil may be so porous or otherwise unfavourable for plant growth that succession is permanently checked at a stage earlier than the climatic climax; under these conditions the vegetation reaches an edaphic or soil climax. An example in the Pacific of what is probably an edaphic climax is the scrub on the serpentine soils of New Caledonia; the climate here would probably allow trees to grow, but the porous and sterile soil prevents it.

Stages in both kinds of succession can be seen on every Pacific island. Particularly good examples of primary successions can be seen on the lava flows of Hawaii. Great rivers of lava have flowed down from the volcanoes, cooled and solidified. In the course of years the lava has weathered and soil has formed on it. Plants have begun to grow, first in the cracks, later on the surface as well. The first plant colonists have helped on the process of soil formation by the action of their roots and by contributing humus, and so brought about improved conditions for their successors. The first plants on these lava flows are algae, mosses and lichens, which require little soil; later come ferns, bushes and small trees, among which *Metrosideros polymorpha* is one of the most important. Finally a tall forest is established. The time taken by this succession and the exact sequence of stages depend, among other things, on the nature of the lava; on the smooth *pahoehoe* lava, plants arrive sooner and the succession proceeds faster than on the *aa* lava, which consists of piles of separate blocks. A very similar primary succession can be seen on

Savai'i in Samoa, where there are also lava flows of different ages; flows 100–150 years old already have trees growing in the cracks or on soil on the surface.

Secondary successions take place when the original vegetation (whether climax or not) has been, for instance, felled, burnt or grazed; almost always they are due to man or to his domestic animals. Since human influence is profound on almost all the Pacific islands, a very large number of the types of vegetation, including some that at first sight seem entirely 'natural', are in fact stages in secondary successions. Secondary, like primary, successions, tend sooner or later towards the re-establishment of the climatic climax. Very often, however, the interference by man or animals continues, and an apparently stable type of vegetation, a biotic climax, results. Most, perhaps all, grassland of the Pacific, except that above the climatic tree limit in the high mountains of New Guinea, and some which may represent stages in primary successions, is probably a biotic climax. It probably occupies the site of former forest and would revert if protected from grazing and fire. (Types of grassland are shown on Plates 39, 42, 45.)

Without careful investigation it is often impossible to say whether a given type of vegetation represents a climatic or a biotic climax. It is nevertheless essential to bear in mind the difference between primary types of vegetation which, when they reach the climatic climax, are for practical purposes stable and unchanging, and the secondary types which depend on the activities of man and domestic animals. These are unstable; they can, and frequently do, change rapidly and completely. This is particularly true of regions like the Hawaiian islands where the great influx of population since European colonization began has had disastrous effects on the native vegetation.

Primary Types in Wet Climates (*Rain Forests*)

Rain forest covers, or did cover at one time, all the land area in the Pacific except some of the coral islands, the tops of the highest mountains in New Guinea and the Hawaiian islands, the dry lee sides of certain islands, and certain other dry areas such as Easter island, parts of New Guinea, and most of New Caledonia. These rain forests, though they are all evergreen and have a superficial similarity, are very varied in character, and knowledge of them is still so incomplete that a satisfactory classification is not yet possible. A rough division can however be made into (*a*) tropical rain forests,

which are tall and luxuriant and composed of a very large number of species of trees, and (*b*) subtropical and montane rain forests, which are less tall and luxuriant and considerably less rich in species. Tropical rain forest occurs in the tropical lowlands where the mean temperature is about 77–79° F., with little seasonal variation. Subtropical and montane rain forest occurs outside the tropics or on mountains within them, and has a lower mean temperature which may show a range of several degrees between summer and winter.

Tropical Rain Forests

These reach their highest development in the Pacific in the lowlands of New Guinea and the neighbouring islands, especially New Britain (Plate 35), the Solomons (Plate 34) and the New Hebrides. Essentially similar forests occur in Samoa (vol. II, Plate 114, p. 587), and on the windward side of the larger Fiji islands. Before the destruction of the original vegetation by man, tropical rain forest doubtless existed at low altitudes in the Society islands, Marquesas, Hawaiian and other 'high' islands, but at the present day what forest is left at low altitudes seems to be secondary.

Tropical rain forest corresponds with the popular idea of a tropical forest and that on the Pacific islands is similar in its general features to the vast rain forests of the Malay archipelago, equatorial Africa and tropical America. It is often described as impenetrable, but as a matter of fact in virgin as opposed to secondary rain forest, the undergrowth is rarely very dense. Except for thick patches where a tree has fallen down, it is possible to move about with little difficulty, though a man is seldom visible at a greater distance than perhaps 20 yd. It is usual to 'cut a path' with a large knife when traversing the forest; this is as much in order to retrace one's steps if necessary as for any other reason. Where there is any kind of break in the forest (for instance where a road or wide river crosses it), the undergrowth does in fact become very dense. The edge of a forest along a clearing, road or river appears as a solid wall of vegetation, but it gives a misleading idea of the forest interior. The air in the forest is extraordinary still, but though the forest is gloomy, the forest floor is dappled with sunflecks. The contrast between light and dark patches is so sharp that it is impossible to take good photographs except when the sun is behind clouds.

Tropical rain forests are not a mass of brilliant and varied coloured flowers. Plants with showy flowers do exist, but they are not common and need looking for. The majority of trees have very

small greenish or whitish flowers, inconspicuous even to the eye of the botanist. The forest as a whole is a sombre green.

The crowns of the trees in a tropical rain forest are arranged in about three superposed layers or storeys, somewhat like the oaks and hazels in an English coppice, though from ground level this is by no means obvious. The topmost storey consists of trees about 100–150 ft. high or perhaps less; the second storey is at about 50–80 ft., and the third at about 25 ft.; below this again are shrubs, saplings and a layer of herbaceous plants, generally thinly scattered, not massed like the primroses and bluebells in an English wood. A unique type of rain forest is found in New Britain. Here the topmost storey is formed by *Eucalyptus deglupta*, a superb straight-trunked tree reaching a height of over 230 ft. The crowns of the *Eucalyptus* are raised far above the second storey and are not visible from the ground.

In all the storeys the trees are mostly evergreen in the sense that their leaves are not dropped all at once, or if they are, the new leaves expand before the old have all gone. Some of the taller trees, however, may be deciduous and are bare for a few days or weeks. They differ from the deciduous trees of colder climates in being less synchronized in their behaviour; where several individuals of the same species are growing side by side, one may be fully green, another bare, another just producing a crop of fresh young leaves. A characteristic feature of rain forest trees is that the young leaves are often brilliant red or purple, and occasionally dead-white like paper; often when they expand they hang down limply as if wilted.

The trees of the top storey have tall straight trunks, thin in proportion to their length; trunks over 3 ft. in diameter are rare. The crown is often rather flattened and when seen in an isolated tree seems disproportionately small. The leaves are commonly oval, undivided and leathery, of about the size, shape and consistency of a laurel leaf.

A striking feature of many of the taller trees (in the first and second storeys) is the plank buttresses which support the base of the trunk. These are thin plate-like outgrowths extending up the trunk sometimes for as much as 20 ft., and outwards along the ground for about the same distance. They add greatly to the labour of felling the trees because a platform has to be built so that the axeman can cut the trunk above them.

The second and third storey trees have much smaller and narrower crowns than those of the first storey; their trunks are of course still

more slender. The average size of their leaves is greater and they are often drawn out into characteristic long fine points at the tips.

Both palms and tree ferns are found in the rain forest but neither are usually very plentiful, though small palms sometimes form a large part of the undergrowth. Tree ferns are usually restricted to fairly high altitudes, and to moist sheltered places, such as ravines.

Besides the trees, shrubs and low-growing herbs, the rain forest includes two groups of plants, both highly characteristic of it, the lianas or woody creepers, and the epiphytes. The lianas, like the ivy, use the trees merely as a support and do not take nourishment from them. They spread from tree to tree, often hanging down in huge loops or festoons and their stems may reach a length of several hundred feet. The leaves and flowers of these lianas are mostly far out of sight among the tree tops. Their stems vary in thickness from that of a little finger to that of a thigh; some are round in section, others are flattened like a gigantic ribbon, others twisted and closely resembling a stout rope or cable. In the rain forests of New Guinea rattans are common; these are climbing palms, often with thorny stems, which because of their great length and strength can be used for innumerable purposes in place of rope or wire.

The epiphytes include many orchids with strange and beautiful flowers and a large variety of ferns. They grow perched up on the trees and like the lianas most of them are not parasites. The only soil available for their roots is the dead leaves which become entangled with them or are brought by ants. Perhaps the most remarkable of the epiphytes are the 'strangling' figs, belonging to the same genus as the edible fig and the banyans. They start life as epiphytes, but soon strike down roots into the ground. In course of time the tree which supports them becomes surrounded by a network of tough roots, eventually it dies and the fig is left as an independent tree, its 'trunk' consisting of a hollow cylindrical network of roots. The life-history of *Metrosideros*, a common tree of montane rain forest in the Pacific, is similar.

By far the most important characteristic of the tropical rain forest, and the one in which it differs most from temperate woodlands, is the enormous number of species of trees composing it. In an English wood the great majority of the trees are, say, oaks, with perhaps a few birches, ashes or other trees intermingled. In a Pacific rain forest on the other hand, as a rule no one species of tree is dominant; there is a mixture of a vast number of different kinds of trees, no

Plate 37. Coniferous forest, Arfak mountains, Dutch New Guinea
The altitude is about 6,700 ft.

Plate 38. Mountain forest, Anggi-Gita, Arfak mountains
The altitude is about 4,500 ft. The trees are mainly species of *Araucaria*.

Plate 39. Vegetation of the dry zone, Oahu

From the summit of Kalama crater looking across the Kalama valley. The valley floor is covered with *Prosopis chilensis*; the lighter coloured vegetation is grassland of *Heteropogon contortus*. The ridge in the background is 1,000 ft. high.

Plate 40. Sub-tropical rain forest, Más-afuera, Juan Fernández

The chief tree is *Murceugenia Schultzei*.

one of which forms a large fraction of the whole number. In the Veimauri forest in Papua, for instance, there were 437 trees of over 5 ft. girth on a 108 acre sample plot; these belonged to 69 species, of which no one formed more than 10% of the total. One may often see only a single tree of a particular species during a whole day's march. The species in each storey are different, though of course those of the lower storey include many young individuals of species which reach the high storeys when fully grown. Though rain forest is normally a fairly even mixture of species, exceptionally a single species may be dominant over a considerable area. Thus along large rivers in New Guinea the magnificent *ilimo* or *erima* (*Octomeles sumatraensis*), may form an almost pure growth. Trees of the family Dipterocarpaceae, which forms a large proportion of the bigger trees in the forests of the Indo-Malayan region, are found in the Pacific only in New Guinea and even there are not particularly abundant.

The hundreds of species of trees forming the rain forests of New Guinea, Fiji, and Samoa include many which furnish valuable timbers and other useful or potentially useful products, such as gums and resins. The great majority, however, have at present no important uses though doubtless future research may discover some. Since the valuable species are found scattered through a mass of more or less useless species, the mixed composition of rain forests is a serious economic disadvantage. The majority of the large trees in virgin rain forests are hardwoods, often excessively hard and so heavy that they will scarcely float in water. Good timbers for constructional work are common and there are also many beautiful ornamental woods, but there are few soft woods which will serve the purpose of deal.

A number of rain-forest trees are poisonous; there is *Antiaris*, for instance, said to be the original of the fabled Upas Tree. The unpleasant nettle tree, *Laportea*, recognizable by its red-veined, stinging leaves, is found in rain forests in the New Hebrides, New Guinea and elsewhere.

Similar in many respects to the tropical rain forests are the *fresh-water swamp forests* which cover a vast area in the low-lying river valleys of New Guinea and New Caledonia, and are doubtless found on a smaller scale in the neighbouring islands. These swamp forests, which are an edaphic climax in which the succession to normal rain forest is prevented by the waterlogging of the soil, are of more than one kind; most are mixtures of broad-leaved evergreen trees, with

or without palms. As a rule, owing to the softness of the ground and the number of lianas and plants with stilt roots, they are extremely laborious to traverse. The most important and perhaps the most widespread type of swamp forest in New Guinea is the sago forest, dominated by palms of the genus *Metroxylon*. These palms provide the staple food for many of the native tribes.

Subtropical and Montane Rain Forests. These differ little from each other, and they differ in degree rather than in kind from tropical rain forest. Subtropical rain forest (Plate 40) is seen on Lord Howe island, the Kermadecs, Juan Fernández (though the forest here should perhaps be termed temperate rather than subtropical) and possibly in a few more islands south of the actual tropics. Montane rain forests (Plate 38) cover the higher ground of most of the 'high' islands, often coinciding fairly exactly with the 'mist zone' which is covered with an almost permanent cloud cap.

Both these kinds of forests are less tall, less luxuriant and composed of far fewer species of trees than the tropical rain forest. They often lack features characteristic of tropical rain forest (for instance the trees generally lack plank buttresses), rather than having characteristic features of their own.

The trees are usually only 60 to 80 ft. tall, often considerably less; rarely they may reach 100 ft. Generally there are only one or two storeys of trees in addition to shrubs and herbs. The trunks are less straight than in tropical rain forest, and thicker in proportion to their length. The crowns of the larger trees tend to be spreading, with a tendency to be umbrella-shaped. An important difference from tropical rain forest is that the average size of the leaves is much smaller; speaking very generally they tend to resemble those of a holm oak rather than those of a laurel. In New Guinea, where a series of zones of forest follow one another from the lowland tropical rain forest to the tree limit at about 14,000 ft., a gradual diminution in the average leaf size with increasing altitude can be noticed.

The number of species of trees, though always less than in tropical rain forest, varies within wide limits. In the subtropical (or temperate) rain forest of Juan Fernández the tree storey proper consists of only three to six species, but in montane rain forest between 6,000 and 9,000 ft. in New Guinea a sample plot of 40 acres had 229 trees of timber size belonging to 24 species. Like the species, the number of families of trees is restricted. Some characteristically tropical families are absent and temperate families appear in their places. The two families most constantly and abundantly present are

probably the Myrtaceae (Myrtle family) and the Araliaceae (Ivy family); both of these however are present, though less conspicuous, in the tropical rain forest. The presence of conifers (Fig. 58; Plate 37) such as *Araucaria* and *Podocarpus* is generally characteristic of montane rain forest in the Pacific; in tropical rain forest conifers are usually absent altogether. The kauri pine (*Agathis*), in the tropical forests of Fiji and Vanikoro is an exception. The abundance of these conifers is variable: in the Hawaiian islands they are absent, but in New Guinea they are plentiful and in the higher mountain forests above about 10,000 ft. become the dominant trees.

Palms and tree ferns are often a conspicuous feature of subtropical and montane rain forests and, though never dominant, may be very abundant, sometimes standing out above the level of the other trees. Lianas are usually much scarcer than in tropical forests, though here again there is much variation. In Juan Fernândez there is only one species of liana, which is probably introduced. Epiphytic flowering plants are generally few in species and may be absent altogether, but epiphytic mosses, liverworts and lichens are nearly always plentiful and are sometimes a conspicuous feature.

It is clear that the types of forest here grouped together as montane and subtropical rain forests are very heterogeneous. Though we do not yet know enough about them to distinguish the different kinds, one or two distinct types stand out from the rest, for example the mossy forest found in the mist zone of islands such as the Marquesas and on the mountains of New Guinea above about 7,500 ft. The trees are only about 20 ft. high and are grotesquely gnarled and twisted. The dripping wet covering of mosses, liverworts and ferns on trunks and branches gives them a fantastically swollen appearance, often making them look twice their real thickness. The soddenness of the vegetation combined with the driving mist and perpetual drizzle make the mossy rain forest a cheerless place. The dense undergrowth and network of aerial roots make it as hard as any type of forest to traverse.

As the mountains are ascended the forest changes in character, becoming, generally speaking, more dwarfed, less luxuriant and less like the tropical rain forest as one goes upwards. The nature of the forest at a given place depends as much on exposure and slope as on actual altitude; thus on exposed ridges and summits on the smaller 'high' islands the rain forest may be reduced to a mere scrub, though the altitude is only some 3,000 ft. Mist forest

similar to that occurring at about 8,000 to 10,000 ft. in New Guinea covers ridges in New Caledonia and the Marquesas which are less than 5,000 ft. high.

In New Guinea and Hawaii the mountains are high enough for the climatic tree limit to be reached and here a series of forest zones from the lowlands upwards can clearly be distinguished. In New Guinea the tropical rain forest is succeeded at about 1,000 ft. by the 'foothills forest', which is less luxuriant and also differs in having fewer lianas, epiphytes and trees with plank buttresses. In the upper part of the 'foothills forest' the first conifers appear. Between 4,500 and 7,500 ft. the foothills forest gives place to the mid-mountain forest', in which the hoop pine (*Araucaria Cunninghamii*) is one of the commonest large trees. Other conifers and two kinds of oak are also plentiful. This is a typical montane rain forest. The next zone, beginning at an average height of 7,500 ft., is the mossy forest, which has already been described. Finally, from about 10,000 ft. to the tree limit at about 14,000 ft. is a drier type of forest

Fig. 60. *Aleurites moluccana*, candlenut tree

A common Pacific islands tree. The leaves have a characteristic frosted appearance. Drawn from E. J. H. Corner, *Wayside Trees of Malaya*, vol. II, plate 55 (Singapore, 1940).

consisting predominantly of conifers (*Podocarpus*, *Libocedrus*, *Dacrydium*, *Phyllocladus*) with some broad-leaved trees intermingled. This zonation depends on the gradual change of climate: with increasing altitude temperature diminishes steadily, but humidity increases up to a maximum in the mossy forest (mist zone) and afterwards decreases.

On the windward (wet) sides of the larger Hawaiian islands three forest zones can be recognized, but the zonation is much complicated by local differences of humidity, slope and terrain (young and old lava, etc.) as well as by the partial replacement of the primary forest by secondary vegetation, so that it is difficult to give exact height limits. All three zones are mixtures of broad-leaved trees without conifers; in the lower zone characteristic trees are the candlenut (*Aleurites moluccana*; Fig. 60), and the *koa* (*Acacia koa*). In the middle zone the *ohia* (*Metrosideros polymorpha*) is characteristic, though it is present all the way from sea-level to 9,000 ft. In the upper zone the species are few and the forest has the general character of mossy forest.

The timbers of the subtropical and montane rain forests are mostly hardwoods, except for those of the conifers, and are like those of the tropical rain forest. The montane rain forests of the Hawaiian islands produce some excellent woods which are exploited on a considerable scale both for local use and export. In the other groups of islands, though there has been much destruction of the forests, the timber has not been made use of on a large scale, mainly owing to the inaccessibility of the forests. Far more important than their possible value as producers of timber is the value of these montane forests as a protection against soil erosion and in conserving and regulating the water supply of the lower, more thickly populated land. This is particularly true in the Hawaiian islands where rain forests often cover slopes which appear to be almost vertical.

Secondary Vegetation of Wet Climates (Secondary Rain Forests, Scrub, Fernbrakes, Grassland)

The types of vegetation which may arise after the destruction of rain forest are many and varied and cannot be described here in detail. In the first place there are the secondary rain forests, which differ from the virgin forest they replace in being lower and generally thicker, and more difficult to penetrate owing to the dense undergrowth and more abundant creepers. The trees are mostly soft-

wooded, rapidly-growing species which are almost worthless economically. The flora of these secondary forests is always poorer in species than that of the original primary forest. When young, secondary forest is easily recognizable, but left to itself it becomes more and more like primary rain forest. Much of the existing rain forest on the 'high' islands of the Pacific is probably secondary—for instance the 'intermediate forest' of the Marquesas, dominated by *Hibiscus tiliaceus*, and all the forest on Rarotonga, except at high altitudes.

Besides the secondary rain forest there are many other types of secondary vegetation which are much less like the original primary forest—for example the scrub formed by shrubs such as the guava (*Psidium guajava*) and the troublesome *Lantana* (Fig. 61), which cover huge areas in both Fiji and Hawaii. Another secondary type is the fernbrake of *Gleichenia* (*Dicranopteris*) *linearis* (Plate 41), a plant which perhaps covers a greater area in the Pacific islands than any other single species. It forms dense thickets 10 to 12 ft. high, which can be penetrated only by hacking a path. In many places it is spreading at an alarming rate; in Kipapa gulch on Oahu (Hawaiian islands), for instance, it is said to be advancing some 3 ft. a year. Finally there are several types of grassland which can arise after the destruction of rain forest. In New Guinea and the neighbouring islands there are large areas of the tussocky *alang-alang* grass (*Imperata*, Plate 45), which also covers much former forest land in the Malayan region. In the Marquesas the introduced grass *Paspalum conjugatum* is tending to replace both the primary rain forest and the 'intermediate forest'. In the Hawaiian islands a number of non-native grasses have established themselves over large areas.

All these secondary types of vegetation are believed to be stages in succession following the destruction of rain forest. The course of these successions may be complicated and will depend, among other things, on the kind and duration of human interference. On islands where the old forest has been entirely destroyed the succession might take a very long time and the forest might never become identical with the original owing to the lack of parent trees to provide suitable seedlings.

A general picture of the origin of secondary vegetation from rain forest can be obtained in New Guinea, where the course of events seems to be fairly straightforward. The natives, as in most tropical countries, practise shifting cultivation. A patch of virgin tropical rain forest is cleared by felling and burning, and one or two crops

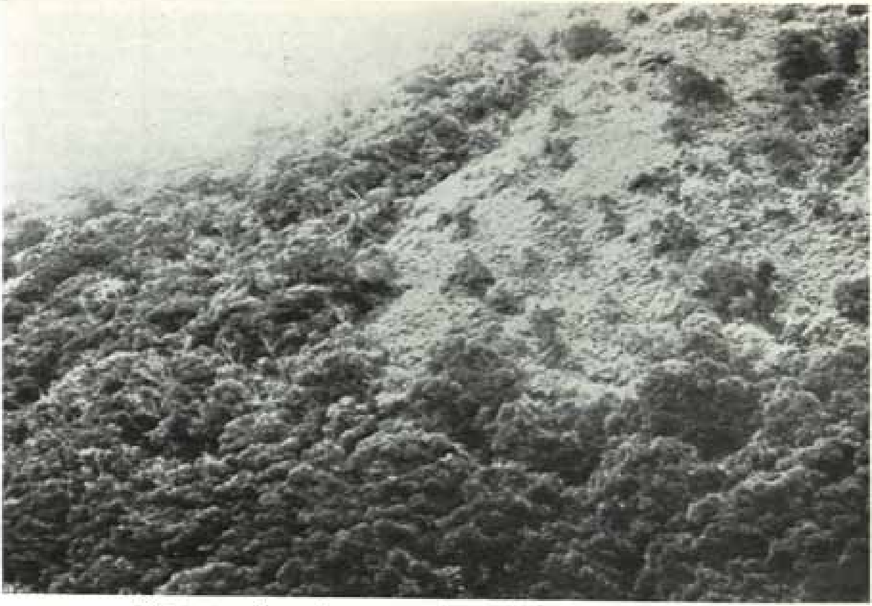

Plate 41. Secondary vegetation, Kuliouou gulch, Oahu

The area is in the zone of *Acacia koa*. Secondary forest of *Psidium cattleianum* var. *lucidum* (a species of guava); light patch, a fern brake of *Gleichenia linearis* with remains of the original tree-cover.

Plate 42. Secondary grassland, upper Ramu basin, New Guinea

This grassland probably replaces former forest; trees survive along the watercourses.

Plate 43. Scrub vegetation, Galápagos islands
Dry season conditions on the limestone plateau near Wreck bay, San Cristobal.

Plate 44. Scrub with cacti, Galápagos islands
Vegetation of the volcanic soils of Chatham island.

of taro (Fig. 62), yams or sweet potatoes (Fig. 68) are grown. The land is then abandoned and in an incredibly short space of time small soft-wooded trees such as *Trema*, *Alphitonia* and various species of *Macaranga* spring up and soon form a dense secondary forest 20 to 60 ft. high. These trees are short-lived and in course of time they are replaced by slower-growing species which have grown up in their shelter. These slow-growing trees are similar to those found in the virgin forest and, after a period, the length of which is unknown, the succession, if undisturbed, would undoubtedly lead back to something very like the original rain forest. The natives however often clear the land again after a lapse of about 8 to 10 years, which gives time for the humus used up in the last brief period of cultivation to be built up again in the soil. Civilized government and peaceful conditions tempt the natives to cultivate the land on a shorter cycle and under these circumstances grasses such as the *alang-alang* tend to invade the area and gradually convert it into useless grassland. The natives cannot cultivate the grassland; they burn it periodically to drive pigs and wallabies when hunting. In this way grassland arises as a biotic climax derived from rain forest. Destruction of forest in ways similar to this has taken place on practically every Pacific island.

Primary and Secondary Vegetation of Dry Climates

In New Caledonia, the dry belts of New Guinea, and on the dry lee side of the 'high' islands, uncultivated land is covered by evergreen forest, scrub or by some kind of grassland or savannah (Plates, 39, 45). The dry types of vegetation are naturally more liable to damage by fire and grazing animals than is rain forest and its derivatives, and probably revert to their original condition more slowly. The difficulty of distinguishing between primary and secondary vegetation is therefore greater than in wet climates, and since our knowledge of the vegetation of dry areas is very incomplete, all that can be done now is to mention some of the chief types of vegetation, leaving their classification to the future.

Dry Evergreen Forest. This is well developed in southern New Guinea and New Caledonia. On the lee sides of the Hawaiian islands a dry type of forest is found above about 1,000 ft., but at lower altitudes the native vegetation of the dry regions has been almost completely replaced by weeds and cultivation. Relics of dry evergreen forest exist in Fiji and the Marquesas; in Easter island, which today is covered with an almost treeless grassland, a

careful study of the vegetation and climate suggests that at the time the island was first colonized by the Polynesians it may have been covered with a forest of the small tree *Sophora toromiro* and perhaps by other endemic trees which are now quite extinct. Many dry areas which are now covered with grassland—e.g., much of the south-east coast of the Gulf of Papua, and the *talasinga* country (i.e., leeward land with a low rainfall) of Fiji—were quite probably forested at one time, but most of the trees have long since disappeared, owing to felling, persistent burning and grazing.

The most typical dry or savannah forests of the Pacific are probably those of New Guinea. The chief trees are species of *Eucalyptus* associated with other Australian trees, such as the paper-bark (*Melaleuca leucadendron*) remarkable for its silvery leaves and thick fissured bark, which peels in thin papery strips. In the foothills, groves of a species of *Casuarina* appear. The whole appearance of these forests is almost exactly like those of the drier parts of Queensland.

A remarkable series of types of dry forest, varying very much in character, is found in New Caledonia. On the one hand there are close evergreen forests with a shade-bearing undergrowth, the trees reaching a height of about 100 ft.; on the other there are open savannah woodlands of *Melaleuca* (here called *niaouli*) with a ground cover of grasses and herbaceous plants. The tall closed forests differ only slightly from rain forests; the trees tend to have rather smaller and more leathery leaves. Lianas, as in the rain forests, are a characteristic feature, but epiphytes and other plants of damp climates are scarce or absent. These dry forests are extremely rich in species, the great majority of which are endemics not found outside the island. A peculiarity of New Caledonia is that though conditions of soil and climate seem much like those of Australia, of the two genera of trees most typical of Australia, the gums (*Eucalyptus*) and wattles (*Acacia*), one has no native species and the other only two in the island.

The native dry forests of the Hawaiian islands have been little described, but it appears that they are of mixed composition and very rich in species, considerably richer than the Hawaiian rain forests. Though the conditions are such that many of the trees would be expected to lose their leaves in the dry season, only three or four species are deciduous, the great majority being evergreen. Lianas are few and the undergrowth is surprisingly scanty. At latitudes up to 2,000 ft. large areas are covered with secondary

Plate 45. Grassland in western Nukuhiva, Marquesas

The chief grass is *Rhaphis aciculata*; note the trees along the watercourse.

Plate 46. Secondary grassland, Buka, Solomon islands

Alang-alang (*Imperata*) grassland usually arises after the destruction of tropical rain forest by shifting cultivation; the surviving forest on the left is probably secondary.

Plate 47. *Myrmecodia*

The plant has been cut longitudinally to show the cavities inhabited by ants.

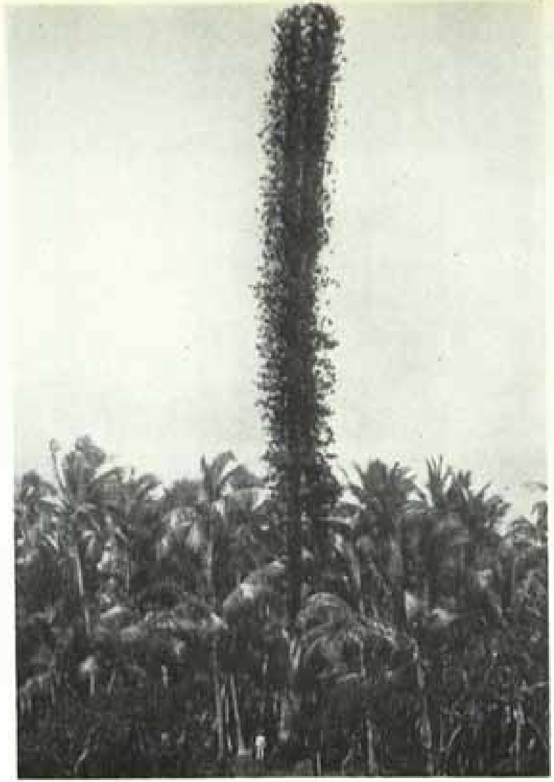

Plate 48. *Araucaria columnaris*, among coconut palms, Yaté, New Caledonia

The Isle of Pines owes its name to this extraordinary conifer. When the botanist Forster saw these trees (on Cook's second voyage), he mistook them for basalt columns.

woodlands of the *algaroba* or *mesquite* (*Prosopis juliflora*), a tree introduced into the island over a hundred years ago and now spreading spontaneously. Some of these woodlands occupy what were once barren dusty plains on which all natural vegetation had been destroyed. The tree supplies food and shelter for cattle, and firewood, and is a valuable protection to the soil against erosion; the *algaroba* woodlands are therefore an exception to the rule that secondary forests are generally of little economic value.

Though extensive thickets of the introduced guava and *Lantana* are a feature of many dry areas in the Pacific, indigenous *scrub* is not widely developed. On the serpentine areas of New Caledonia there is a very interesting scrub, which as already pointed out, is probably an edaphic climax depending on the peculiar soil conditions. It consists of bushes growing scattered or in clumps, with bare ground between. The number of species is enormous; almost every bush seems to be different from all the others. A characteristic of many of them is that the leaves are either hairy or else extremely shiny, sometimes looking like polished metal. Almost all the species in this scrub are endemic and many are of great botanical interest, but except to the botanist the scrub is a useless wilderness.

Scrub of a very different kind is the characteristic vegetation of the Galápagos islands (Plates 43, 44), except at high altitudes where the damper climate allows the growth of montane rain forest. This scrub consists largely of cacti and other thorny plants. Though many of the species are endemic, the general appearance is much like that of thorn scrub in semi-arid districts of South America.

Dry open woodland such as the *Melaleuca* savannah woodland of New Caledonia grades insensibly into *savannah*, and savannah into treeless grassland. Typical savannah, consisting of open grassland with clumps of trees and bushes, covers large areas in southern New Guinea. The *talasinga* country of Fiji, in which the ground is mainly covered with the tall reed-like grass *Miscanthus japonicus* (or possibly *M. floridulus*) is very similar. Savannah also exists in the dry parts of the Marquesas and in Tonga. In Yap (Carolines) there is a savannah consisting of a mixture of grasses and many herbaceous plants with great numbers of unevenly scattered pandanus trees. In savannah areas the rivers and streams are generally marked by a line of trees or belt of forest, the so-called gallery forest, the growth of which is made possible by the moisture in the soil (Plate 42).

Grasslands of native species are found in the Marquesas and in

Easter island. The grasslands of the Marquesas (Plate 45) are of considerable botanical interest as the grasses of which they are composed are endemics whose nearest relatives are believed to be American. As well as growing on areas which are kept deforested by grazing, they grow on the sea cliffs where erosion is so rapid that trees cannot establish themselves. Sheep and cattle graze on these native grasslands, but the more important cattle-raising industries of Hawaii and New Caledonia depend on artificial grasslands composed of introduced grasses.

Vegetation of High Mountain Summits

In the New Guinea mountains at a height of about 12–14,000 ft. the trees at last disappear, giving place to alpine grassland, bogs, low scrub and bare rock, with snow fields and glaciers on the very highest summits. In many places the apparent natural tree limit is due to the destruction of the forest by native hunting fires, but the true climatic tree limit seems to be reached at about 14,000 ft. On the highest Hawaiian volcanoes the tree limit is at about 8,000 to 10,000 ft., and above this there is mostly lava sparsely covered with scattered bushes and herbaceous plants. Some summits have a peculiar and interesting bog vegetation, including among other plants one of the English species of sundew (*Drosera*). Both the New Guinea and the Hawaiian high mountain flora is interesting, chiefly because of the number of species it contains which are identical with, or nearly related to, plants usually found much further north. Thus in New Guinea there are rhododendrons and gentians like those of the European Alps; in Hawaii the alpine flora includes relatives of the European buttercups, wood sanicle and wild geraniums.

HISTORY OF THE VEGETATION

No one can study the vegetation of the Pacific islands without speculating about its origin. How were these islands, some about 1,000 miles from any other land, stocked with their plant population? Where did the plants come from? What changes has the flora undergone in historic times and in the geological past? The answers to all these questions must be very incomplete and hesitating because on all of them expert opinion is far from unanimous. It is mainly in the study of plant distribution and dispersal that the

Plate 49. Fruit of *Pandanus mei*
The seeds are edible. The pulp of the fruit is fermented to make a drink and is used as food in times of famine.

Plate 50. *Tournefortia argentea*, the tree heliotrope
This photograph is of a tree growing on the shore at Whitesands, Tana, New Hebrides.

Plate 51. The mangrove *Rhizophora mucronata*
The stilt roots are characteristic of the genus. Note the scattered mangrove seedlings in the deeper water in the background.

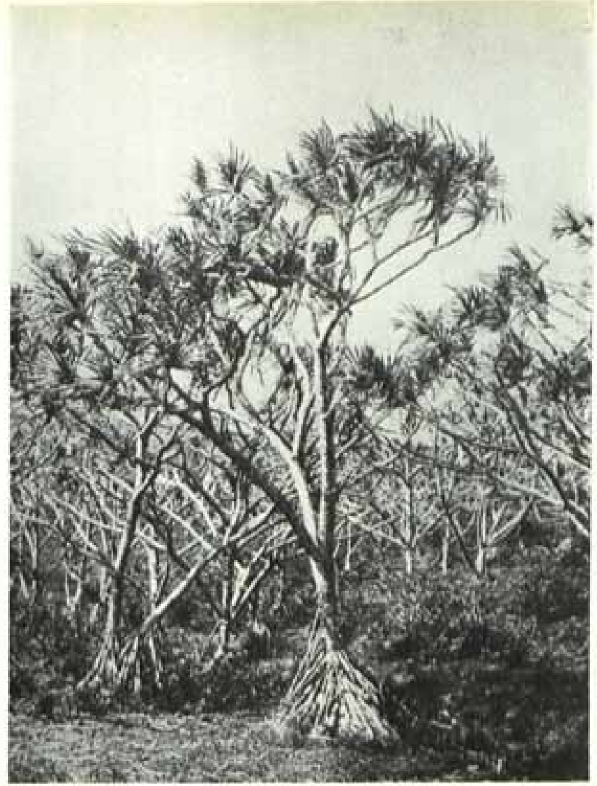

Plate 52. A forest of *Pandanus odoratissimus*
This forest is in the east of Maui, Hawaiian islands. Note the characteristic stilt roots. *P. odoratissimus* is one of the most widespread and widely used plants of the Pacific islands.

answers to these problems must be sought, because up to now geological evidence has proved very disappointing. Since the problems of animal life in the Pacific are very similar to those of the plants, the distribution of animals must be studied side by side with that of the plants.

Theories of Origin

Two fundamental facts must be considered at the start. First, there is, as has already been seen, a striking difference between the flora of the coral islands on the one hand and that of the 'high' islands, including New Guinea, on the other. On the coral islands the flora consists mainly of widely distributed species, many of them found not only throughout the Pacific, but in other parts of the tropics as well. Nearly all these species have seeds or fruits which could be easily carried by birds, wind or ocean currents, and for some of them there is direct evidence that they are so carried and can establish themselves when they arrive. The coral islands are probably all, geologically speaking, very young and their flora mostly consists of recent immigrants. The 'high' islands are quite different; in addition to the wide-ranging species found on the coral islands, there are many more, a large proportion of which are endemics limited to a single island or group. New Guinea is an ancient land mass; the 'high' islands of Polynesia which are volcanic and therefore cannot be dated with any accuracy, though perhaps not very old in the geological time-scale, are certainly old compared with the coral islands.

The second fact which has to be considered is that the islands of the Pacific fall into two groups, those east and west respectively of a line running east of New Zealand, near Tonga, east of Fiji, the New Hebrides and Solomons, and north of New Guinea. West of this line the islands all rise out of comparatively shallow seas and many of them are connected with each other or with the neighbouring large land masses by submarine ridges. Those to the east, on the other hand, rise out of the great Pacific depression, an area of sea over 2,200 fathoms deep (Fig 6, p. 11), or from the Albatross plateau beyond it. As far as the islands west of the depression are concerned, there is no serious division of opinion; it seems clear that they received their present population of plants and animals either across connecting land-bridges which have now disappeared under the sea, or across fairly narrow stretches of open water. Even here there are many mysteries to clear up; how, for instance, are we to

explain the presence in Lord Howe island of *Moraea*, a genus of the iris family, the other species of which are all found in South Africa and Madagascar? Some at least of these western islands have been isolated for a very long time, as is shown by the high percentage of endemics in New Caledonia.

On the origin of the flora and fauna of the islands rising from the Pacific depression and the Albatross plateau there are, broadly speaking, two views. The one is that the depression was once occupied by large masses of land which disappeared in the late Secondary or early Tertiary Period leaving relics of its plant and animal life on the present 'high' islands. Opposed to this is the view that the 'high' islands rose up from a depression which has never contained any large land masses and that the plants and animals found on them are waifs which have been carried over the sea by winds, birds and currents—that is, by the same means as those by which plants have reached the coral islands, but operating over a much longer period.

There are strong arguments in favour of both views and both have to meet difficulties which at present seem insuperable. There is no definite geological evidence in favour of the former existence of land masses in the Pacific depression. The chief arguments for the migration of the flora and fauna by means of land connections are: firstly the difficulty of understanding how, for instance, the relatively rich flora of the Hawaiian islands could have crossed some 1,000 miles of ocean with only the means of dispersal available at the present day; and secondly the existence of an 'Old Pacific Element', a group of apparently very old species which have no near relatives on any of the continents bordering the Pacific. There are also striking resemblances between the flora of extremely distant islands, e.g., Hawaii and the Marquesas, Juan Fernández, and the Western Pacific islands. Against this must be set facts like these:—(i) the Hawaiian islands and most other islands in the depression have no large land animals, except bats, which are not certainly introduced; (ii) islands of the depression have a striking lack of heavy-seeded plants (e.g., the nutmegs, *Myristica*, which are not found east of Samoa), except those which grow on the seashore and have seeds or fruits which float; (iii) the animals and plants are nearly all species which at least theoretically might be carried by the means assumed; (iv) the fauna and flora of the islands includes many 'gaps'—that is, whole families which are present on the surrounding continents are absent for no apparent reason, the

missing families being usually the same on all the islands. At the same time there are other difficulties on the other side. Thus the *Lobelioideae* and land snails of the Hawaiian islands are often found only on one island: if their ancestors were carried over some 1,000 miles of sea, why are the present-day species apparently unable to cross only a few miles?

Whether the migration was mainly overland or mainly by sea, it is clear, as has already been stated, that the bulk of the Pacific flora originated in the Indo-Malayan region, smaller contingents coming from Australia and from South America. There is also much evidence that the continent of Antarctica, which was probably once covered with vegetation, and not with ice as now, was a source from which Polynesia, as well as Australia, New Zealand, southern South America and possibly South Africa received some of their flora.

The flora of the Pacific must be pictured as arriving in successive waves of immigration over a very long space of time. The last wave has been the cultivated plants and weeds brought by Polynesian, Asiatic, and European inhabitants. The plants thus introduced deliberately, and still more the weeds introduced accidentally, bid fair to transform the whole appearance of the vegetation over the greater part of the Pacific.

Cultivated Plants

When the Polynesians spread over the Pacific they brought with them the chief cultivated plants of their original home in south-eastern Asia, such as coconuts, yams and taro. It was their skill in transporting and cultivating these plants, as well as their seamanship, which made their long voyages and successful colonizations possible, for no important food plants except the species of pandanus (Plates 49, 55) and perhaps the breadfruit were natives of the islands to which they came. Most of these cultivated plants were brought to the islands so long ago that they have given rise to many local varieties, each food plant having a 'centre' where its varieties are mainly concentrated—e.g., taro in Hawaii, yams in Fiji, breadfruit in the Marquesas. The history of the sweet potato is much more obscure than that of the other chief food plants. The botanical evidence indicates, without any doubt, that its original home was tropical America, but it is known to have been widespread in Polynesia in the eighteenth century and the Maori of New Zealand cultivated some 25 varieties of it. It is uncertain whether it was introduced by Spanish voyagers in the sixteenth or seventeenth

centuries or whether it is the outcome of a far earlier cultural contact between America and Polynesia.

The tobacco plant, which also originated in America, was probably introduced into the Pacific area in the sixteenth and early seventeenth centuries from Amboina and the Philippines to which it had been brought by the Portuguese and Spanish.

After Cook's voyages a vast number of food, ornamental and other cultivated plants were introduced into the Pacific and are now as much part of the landscape as the much older Polynesian introductions. Many, such as the commercial varieties of the sugar cane, citrus fruits and the pineapple, are important crops, but unlike the taro, breadfruit, etc., they are grown more for export than for subsistence.

Weeds

Weeds, which are so conspicuous a feature of most Pacific islands, have been introduced both by Polynesians and by Europeans, but the great majority are European introductions of quite recent origin. In a recent census of the weeds on the leeward coasts of Fiji, it was estimated that nearly half the species had arrived since 1900. Most of these weeds have been brought in unintentionally but some, like the guava, are cultivated plants which have run wild; a few, like Koester's Curse (*Clidemia hirta*) have been christened with the name of their well-intentioned introducer. A surprisingly large number of Pacific weeds are of American origin, but there are also many which come from southern Asia.

The impression that the weeds are actively suppressing and driving out the native flora is probably largely false. Introduced plants are rarely seen in undisturbed natural vegetation, though *Crepis japonica* now grows in the depths of the rain forest in Hawaii. Even in the open vegetation on lava flows in Hawaii, where there must be plenty of room for newcomers, there are very few introduced plants. The weed flora only becomes aggressive when the native vegetation has been destroyed or damaged; thus guava and *Lantana* only invade rain forest when it has been felled or burned. They replace but do not actually suppress the native vegetation.

One reason for the extreme vigour of some of these introduced plants in the Pacific islands is the absence of their natural insect enemies, which have been left behind in their native homes. Attempts are being made to introduce these insects and thus to right the

balance of nature by 'biological control'. Thus in Fiji *Clidemia* is being successfully checked by an introduced thrips; *Agromyza lantanae*, a fly with a seed-eating larva, and *Thecla agra*, a butterfly with a flower-eating caterpillar, have been recently introduced in the hope of checking *Lantana*.

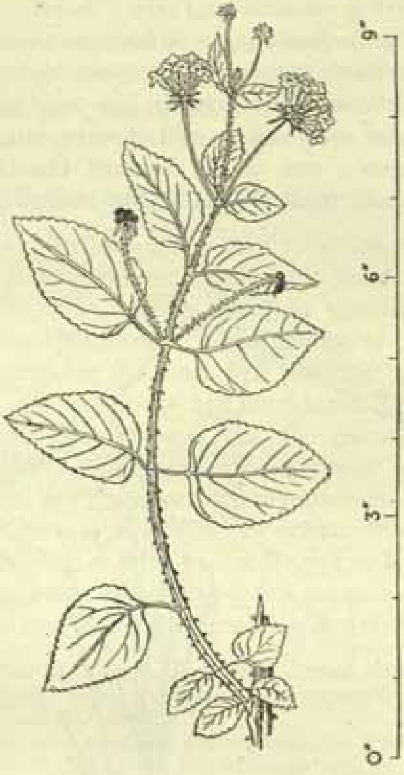

Fig. 61. *Lantana camara*

A shrub of American origin which has run wild and is now a pest in Fiji and other Pacific islands. The flowers are pink, orange or mauve. Drawn from a specimen in the Cambridge University Herbarium and from N. L. Britton, *Flora of Bermuda*, p. 314 (New York, 1918).

As a result of the destruction of the natural vegetation and its replacement by weeds a considerable number of native plants have become extinct. In Hawaii it is estimated that several hundred species have vanished since cattle were introduced. Many more are on the verge of extinction. Thus of the three species of *Hibisca-*

delphus, a handsome genus of trees known only from Hawaii, two were represented in 1913 by only a single living individual and the third by about a dozen trees.

Man and his domestic animals are not only wiping out many native species in the Pacific and converting large areas of beautiful and potentially useful natural vegetation into thickets of useless weeds, but converting valuable land into a desert. An example of a man-made desert is the *fenua ataha* or *terres désertes* in the Marquesas —land which has been deforested by goats and cattle, and now, owing to long-continued over-grazing, has very little vegetation of any kind. A similar story can be told of many other Pacific islands. For example, Laysan, one of the leeward Hawaiian islands, was covered in 1896 with good grassland and bushes 6 ft. or so high;

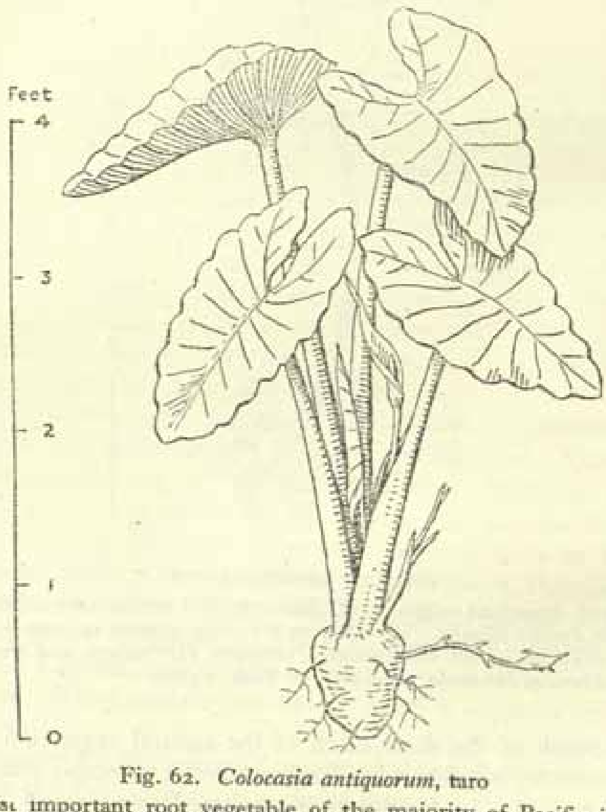

Fig. 62. *Colocasia antiquorum*, taro

The most important root vegetable of the majority of Pacific islanders. Based on *Botanical Magazine*, vol. CXX, plate 7364; vol. CXXVI, plate 7732 (London, 1894, 1900).

the flora numbered 26 species. By 1911, chiefly owing to the swarms of introduced rabbits, many of the native plants had been exterminated. In 1923 the whole island had become a waste of sand, with almost no vegetation. Only four species of plants were left and the Laysan sandalwood tree, known from nowhere else in the world, was represented by only a few dying stumps sticking out of the sand.

The history of Laysan and of many other Pacific islands shows that here, as in many other parts of the world, there is a great need for the understanding and rational exploitation of the natural vegetation.

NOTES ON SOME COMMON PLANTS

It may be useful to give here a few brief notes on some of the commonest plants to which reference has been made in this chapter and of which most of the names recur in various sections of the later volumes of the Handbook. The selection is necessarily rather arbitrary; it excludes for the most part plants found only in cultivation, but some of the species are introduced plants which have become naturalized. For convenience, the descriptions are given in alphabetical order. Some common European and native names are listed, but there are many other native names, especially in the Western Pacific, which it is difficult to extract from the literature, which are very localized, or which are still unrecorded. Some indication of the varied uses to which the native peoples put many of the plants is given, but here also the information is still far from complete.

Aleurites moluccana (Fig. 60. European name, candlenut; Hawaiian, *kukui;* Tahitian, *tutui, tiairi;* Tongan, Rarotongan, Futunan, *tuitui;* Fijian, *lauthi, tuitui, sekethi, sikethi*).

This tree, though now common throughout the Pacific, was probably originally introduced by man from the Malayan region. The nuts, which are very hard, contain an oily kernel, which is edible in small quantities. In former times, kernels threaded on a rib of coconut leaf were used as a taper or candle. The tree is tall and easily recognized by its drooping spear-shaped leaves, which are about 4 to 12 in. long and have a characteristic frosted appearance. The wood is coarse and soon decays. In Fiji, the bark is used medicinally.

Alocasia (European name, giant taro; Rarotongan and many other Polynesian dialects, *puraka;* Futunan, Tikopian, *pulaka;* Samoan, *pula'a;* Gilbert islands, *babai;* Fijian, *ndranu*).

This plant, of which two species are cultivated in the Pacific, resembles taro (*Colocasia*) but is much larger and shows a short stem above ground. It commonly grows to a height of 6 to 8 ft., and has large heart-shaped. strongly-veined, shiny leaves, and a fleshy corm a foot or so in diameter.

The leaves are used as wrappers for food, and also as umbrellas when it rains. The corm, which is hard and woody in appearance, is cooked for food; it is a staple of diet in some central equatorial islands.

Artocarpus incisa (European name, breadfruit; Tahitian name, *uru*; Tongan, Futunan, Tikopian, *mei*; Mangarevan, *tumei*; Fijian, *kulu, uto*; Trobriands, *kum*).

This is a cultivated tree which propagates itself mainly by shoots that spring from the roots. It grows usually to about 30 ft. but old trees may reach 40 or 50 ft. The trunk is slender, with many branches, sparingly covered with very large dark green glossy leaves up to 18 in. long; these are deeply divided into 'fingers'. There are a number of varieties of breadfruit recognized by the Polynesians, each with its own name. The fruit varies in size from that of a large orange to that of a football; it has a tough, rough rind and a soft flesh with a large core holding several seeds. The fruit is inedible when raw and if cut exudes a milky juice; when cooked it has somewhat the consistency but little of the flavour of bread. It is one of the staple foods in some Pacific islands. The leaves are much used for wrapping food, and the wood, which is red and durable, is used for a number of purposes, including house posts and canoes. An adhesive sap obtained from the tree is used as bird lime and as a caulking material for canoes. In Tahiti in former times a choice type of native cloth was made from the inner bark of some varieties of the tree. *Artocarpus integrifolia* (jackfruit), somewhat resembling breadfruit, also grows in some parts of the Pacific, but is more common in the Malayan region.

Barringtonia asiatica (=*B. speciosa*. Tahitian name, *hutu*; Tongan, Samoan, etc., *futu*; Fijian and Melanesian generally, *vutu*). This is a tree growing on sandy beaches, sometimes 60 ft. or more high, but usually shorter. The large four-sided fruits float in sea water and are one of the commonest objects of the drift on Pacific shores. The leaves (Fig. 55) are shiny and leathery and borne in rosettes at the ends of the twigs; they are 6 to 18 in. long. The flowers are about 6 in. wide, with a great tassel of pink-tipped stamens. One or two other species of *Barringtonia* grow in similar situations. The leaves are used medicinally in Fiji, and the wood, which is white, coarse and buoyant, is used in Tahiti for canoes. Generally throughout the Pacific the narcotic seeds of the fruit are used for stupefying fish to assist in taking them for food.

Broussonetia papyrifera (European name, paper mulberry; Maori, *aute*; Marquesas, Niue, *hiapo*; Uvea, *hiapo, tutu, lafi*; Futuna, *lafi*; Tikopia, *fakamaru, mami*).

This tree is probably a native of south-east Asia, but it is almost universally cultivated in the Pacific, and often looks wild. The tree resembles the mulberry, to which, however, it is not closely related. The leaves (Fig. 63) are thin, with toothed edges, and sometimes oval and pointed, sometimes divided into three. The straight trunk is used for poles, but the most important use of the tree, especially in former times, was as a source of cloth (commonly known as *tapa*, or in some areas as *siapo*). This is made by steeping the inner layers of the bark in water and beating them out with a hard-wood mallet.

Calophyllum inophyllum (European name, native almond; Tahitian, *tamanu, ati*; Tongan, Samoan, Uvean, Tikopian, *fetau*; Futunan, *tilo*; Fijian, *ndilo, ndamanu*; Pukapuka, *wetau*).

This is a widespread sea-coast tree growing to a height of 30 to 60 ft. (Plate 30); when old the trunk becomes very thick and the tree has a

wide, much-branched crown, usually leaning towards the sea. The leaves are oval (Fig. 56), rounded at the tip, and are leathery with a shiny surface and very numerous fine, parallel-sided veins. The fruit is round and hard. In Tahiti, the leaves when young and fresh are used medicinally, as also the oil from the seed kernel. In Fiji, this oil is used as a liniment for

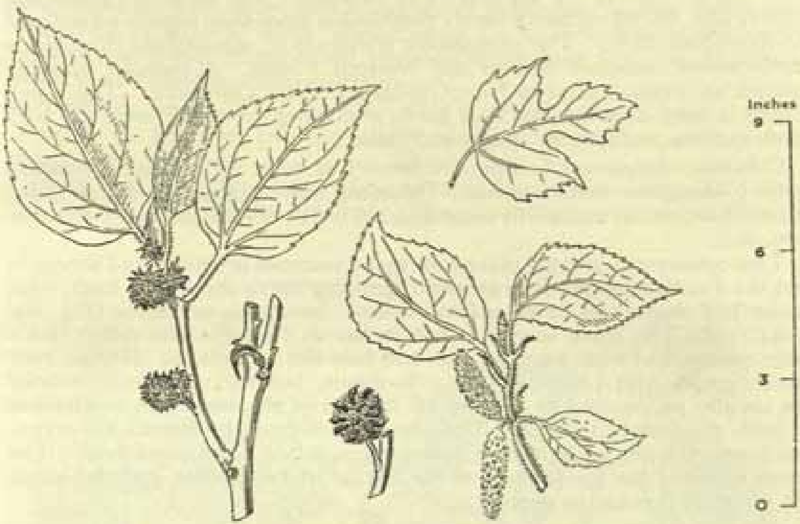

Fig. 63. *Broussonetia papyrifera*, paper-mulberry tree

One of the most commonly cultivated trees of the Pacific islands. The leaves vary in shape, being sometimes divided like that shown in the top right-hand corner of the figure and sometimes undivided. The right-hand twig bears male flowers, the others female flowers. Based on *Andrew's Botanical Repository*, vol. VII, plate 488 (London, 1797); and *Botanical Magazine*, vol. L, plate 2358 (London, 1823).

rheumatism, and the juice from the leaves for relieving eye irritation. The timber which is light pink in colour, and hard, is used in cabinet-making in Fiji; throughout Polynesia it is commonly used for canoe-hulls and wooden bowls.

Carica papaya (European name, papaya, pawpaw; Fijian, *oleti*, and *seaki* or *maoli* in some districts; Tikopian, *naporo*).

This tree (Plate 54) was introduced from America into the Pacific by the early voyagers, and has spread rapidly, especially in areas of secondary growth. It grows as a rule to about 12 to 15 ft. high, with a light pithy trunk, often unbranched to the top. The leaves, which are crowded at the top of the trunk, are large and deeply divided, rather like those of the common fig. The fruit, about the size of a melon, though somewhat less rounded, is dark green until ripe, when it becomes a bright yellow colour; the flesh is somewhat melon-like, but there are a large number of small black seeds in the centre. The fruit and seeds contain a certain amount of pepsin. The milky juice of the unripe fruit is used in Fiji as a remedy for dyspepsia, and the inner bark of the root as a remedy for neuralgia.

Casuarina (European name, Australian oak, she-oak, ironwood; generally in Polynesia, *toa*; Tahitian, *'aito*—because a personal name with the word *toa* in it was adopted about two centuries ago by the Pomare family of chiefs, and respect for them made the people change the name of the tree).

Trees of this genus are distantly related to the English oaks, beeches, etc., but have more the appearance of conifers. The twigs are green and switch-like, the leaves being barely perceptible since they have been reduced to very small teeth. The commonest species is *C. equisetifolia* (Fig. 66), a characteristic seashore tree in the Western Pacific. A number of other species are found inland in New Guinea and New Caledonia. The wood, which is very close-grained and hard, was formerly widely used for bark cloth mallets, and also for spears and clubs.

Colocasia antiquorum (commonly known as *taro*, its general Polynesian name; Mangaian name, *mamio*; Futunan, *talo*; Pukapuka, *wawa*, *talo*; Fijian, *kalo*, *ndalo*, *ndoko*—in some districts only; Trobriands *uri*; Blanche bay, *pa*).

This common cultivated plant with many varieties is widespread throughout the Pacific islands. It is an aroid, growing up to about 4 ft. high, with fleshy leaf stems and large smooth-veined, heart-shaped leaves (Fig. 62, Plate 115). The corm is oval, a few inches in diameter, and rather like a large potato, but with a coarser skin and hair-like rootlets. In Hawaii, *taro* which grows wild propagates by side-shoots, but the cultivated varieties are usually propagated by cutting off the top of the corm and re-planting it, with the attached leaves. The plant varies in its preference for water, but most varieties are grown in swampy ground or in irrigated land. The corm is one of the staple foods of the Pacific island peoples, and the leaves are often also cooked as greens.

Fig. 64. *Inocarpus edulis*, Tahitian chestnut

A large evergreen tree with edible nuts. The flowers are whitish. Drawn from a specimen in the Cambridge University Herbarium and from E. J. H. Corner, *Wayside Trees of Malaya*, vol. 1, p. 395 (Singapore, 1940).

Cordia subcordata (Tahitian name, *tou* ; common names in Polynesia, *tou*, *kou* or *kanava* ; Pukapuka, *wakanava* ; Fijian, *kaunimbuka*).

This is a small, rather bushy tree, usually 15 to 30 ft. high, but sometimes more, with oval, bluntly pointed leaves 3 to 6 in. long. It is in general much like both *Hernandia* and *Thespesia*, but is quite distinct from either in its trumpet-shaped orange flowers. The tree in some parts of the Pacific is thought to have been introduced at an early date by the Polynesians, who value its durable, easily worked wood for building houses and canoes. In Fiji, the sticks were rubbed together to produce fire. In Tahiti, the wood is now used by cabinet-makers.

Cordyline terminalis (commonly called *ti* in Polynesia and Fiji ; Uvean, Tongan, *si* ; Futunan, *tsi* ; the closely related *C. australis* is called cabbage tree in New Zealand).

This is a palm-like plant with a branched trunk, growing up to about 12 ft. high, with a long tap-root. The drooping leaves, unlike those of

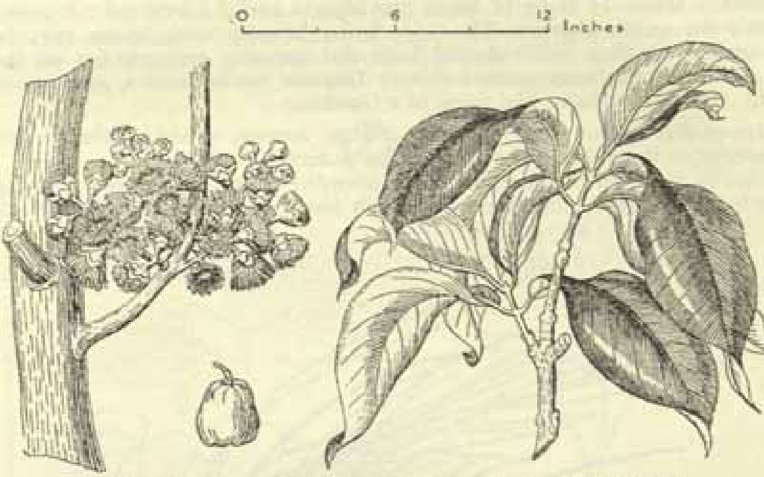

Fig. 65. *Eugenia malaccensis*, rose apple, Malay apple

A tree in which the flowers are borne on the lower leafless part of the twigs. The flowers are crimson and the pleasant slightly acid fruit tinged with pink or crimson. Based on *Andrew's Botanical Repository*, vol. VII, plate 458 (London, 1797).

palms, are sword-shaped and undivided. This is one of the important economic plants of the Polynesians, who use the leaves as wrappings for fish, etc., and the root as a food. A fermented drink is sometimes also prepared from the root, which is very sweet when cooked.

Dioscorea (European name, yam ; known generally in Polynesia as *uwhi*, *uhi* or *ufi*, according to dialect, but some large varieties are termed *kape* or *'ape* ; Fijian, *kawai*, *kaile*, etc. There is a great range of Melanesian and Papuan names for the yam.)

Yams are climbing plants (Plate 116), with tubers, but there are many species and varieties, both wild and cultivated. Some have aerial as well as subterranean tubers, but the tubers of most are subterranean only. The

latter vary greatly in size. Many are about as big as a very large potato or dahlia root, but others are long and comparatively thin. Some tubers grow to a huge length—examples measured have been 10 ft. and 11 ft. long, and nearly as thick as a man's thigh. The leaves of the plant are usually heart-shaped and small, averaging about 6 in. long. The tubers of many kinds are one of the staple foods of the Pacific, especially in Melanesia and parts of New Guinea, but some of the wild types are useless and even poisonous.

Eugenia malaccensis (European name, Malay apple, rose apple; Tahitian, *'ahia*: Hawaiian, *ohia*; Fijian, *kavika*; Tikopian, *kafika*).

This tree grows to a height of about 60 ft., and has large dark green drooping leaves (Fig. 65). The crimson-pink flowers grow in clusters on the branches behind the leaves. The fruits are about 2 in. long, pear-shaped or oblong, and either crimson or white splashed or striped with crimson; they are juicy and have a pleasant, slightly acid flavour.

Guettarda speciosa (Fijian name, *mbuambua*; Gilbert islands, *uri*).

This is a tree 15 to 30 ft. high, providing a useful hardwood; it grows mainly on sandy shores. The very large, broadly oval, leaves may be recognized by their heart-shaped base and opposite arrangement on the twigs. The tree bears masses of very fragrant white flowers, opening at night; they are tubular like those of a *Gardenia*.

Hernandia ovigera (=*H. peltata*. Fijian, *evueva, uviuvi*; Tokelau and elsewhere in Polynesia, *puka*; Pukapuka, *pukama*).

This is a tree of the seashore, with rounded crown, sometimes growing to a height of 45 ft., but generally much less. It can be known from all

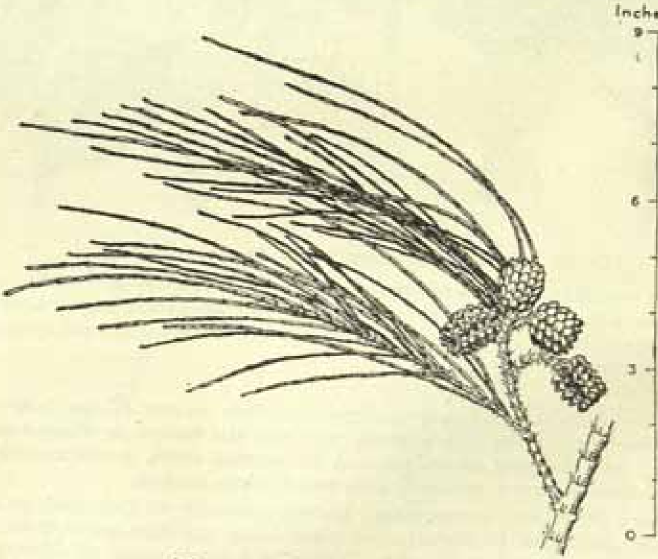

Fig. 66. *Casuarina equisetifolia*

A tree with green, apparently leafless twigs. A common species on sandy beaches in the warmer parts of the Pacific, sometimes planted inland. The figure shows the cone-like female inflorescence. Drawn from various sources.

other common trees of its habitat by the pointed, red-veined leaves, with the leaf stalk attached towards the middle, as in the garden *Nasturtium*. In Fiji, the fruits are used medicinally, and in Polynesia generally the timber is often used for canoe floats, being light and straight-grained, though not very durable.

Hibiscus (named generally in Polynesia *hau* or *fau*; Tahitian, *purau*, *fau*—formerly also *hau*; Mangaian, *'au*; Niue, *fou*; Fiji, *vau*).

The garden hibiscus, *H. rosa-sinensis*, is one of the commonest cultivated shrubs, as in most other parts of the tropics, but it is probably not a native of the Pacific. Of the several native species the most important is *H. tiliaceus* (Fig. 67A). It is a much branched shrub or tree, sometimes reaching a height of 30 ft. It is a characteristic plant of muddy places by the sea or by brackish water, and also often forms the main constituent of extensive woods inland, as in Tahiti and the Marquesas. It and the coconut are by far the most important fibre-producing plants of the Pacific. From the inner bark string and rope are manufactured by the natives, and pads of it are used as wringing material, when coconut cream is expressed or kava made (vol. II, p. 617). In Tahiti the finely braided fibre was formerly made into clothing. The wood is used in boat-building and house-building and for canoe paddles, as well as for firewood. The flowers, which are yellow with a maroon eye, are like those of *Thespesia* (Fig. 67B) and are

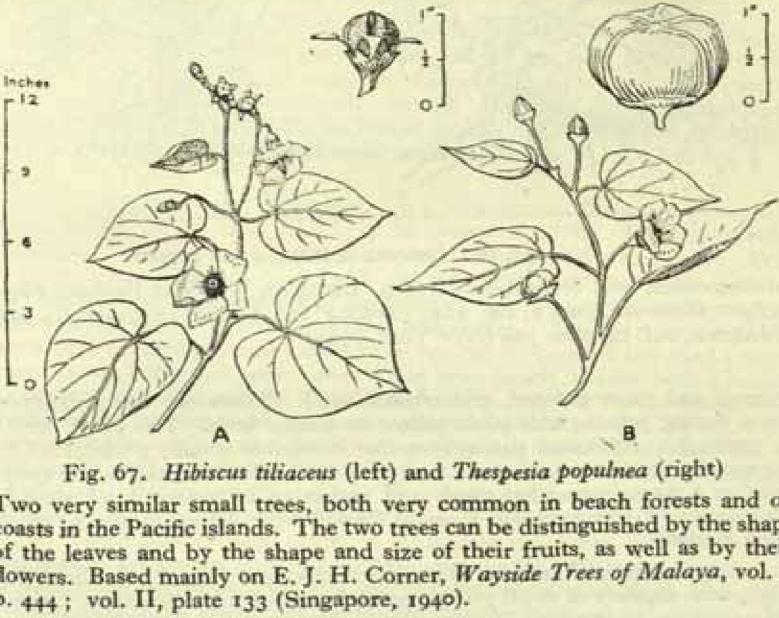

Fig. 67. *Hibiscus tiliaceus* (left) and *Thespesia populnea* (right)

Two very similar small trees, both very common in beach forests and on coasts in the Pacific islands. The two trees can be distinguished by the shape of the leaves and by the shape and size of their fruits, as well as by their flowers. Based mainly on E. J. H. Corner, *Wayside Trees of Malaya*, vol. I, p. 444; vol. II, plate 133 (Singapore, 1940).

often worn as ornaments. The leaves are similar in shape to those of the English lime tree, with a felt of grey hairs beneath; in the Cook islands they are used as plates.

Inocarpus edulis (Fig. 64. European name, Tahitian chestnut; Tahitian, *mape*; Tonga, Rarotonga, Tikopia, etc., *ifi*; Mangaia, *i'i*; Fijian, *ivi*).

This tree commonly grows to a great height, often reaching 60 ft. The

leaves are leathery and elliptical, with tapering points, and sometimes are as much as 14 in. long. The fruits, hanging singly or in clusters from slender twigs, are of an irregular kidney shape, with one seed in a thick fibrous pod, which is several inches long. The seeds, which are commonly used as food, especially when root crops are scarce, taste rather like chestnuts when cooked. The bark of the tree gives out a red sap when cut. The trunk, like that of many other tropical trees, has thin flanges or buttresses, which were often beaten as gongs in olden days. The timber is tough, but because of the size of the buttresses is of little commercial value.

Ipomoea batatas (Fig. 68. European name, sweet potato; Maori, Rarotongan, *kumara*; Tongan, *kumala*; Tahitian, '*umara*; Samoan, '*umala*; Hawaiian, '*uala*; Mangaian, *kuara*; Fijian, *kumala*, *kawainivulagi*).

This creeping plant is a convolvulus, with deeply divided leaves about 6 in. long, and subterranean tubers rather like those of the potato, though

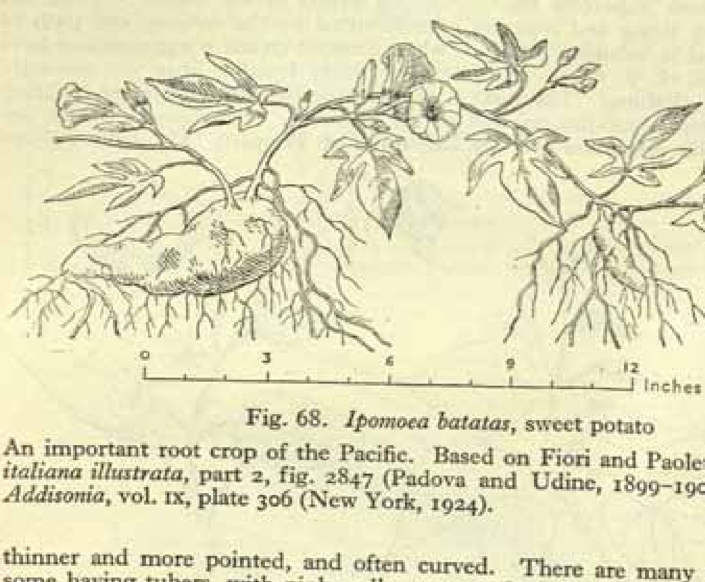

Fig. 68. *Ipomoea batatas*, sweet potato

An important root crop of the Pacific. Based on Fiori and Paoletti, *Flora italiana illustrata*, part 2, fig. 2847 (Padova and Udine, 1899–1904); and *Addisonia*, vol. IX, plate 306 (New York, 1924).

thinner and more pointed, and often curved. There are many varieties, some having tubers, with pink, yellow or purple flesh. The plant, which is commonly cultivated throughout the Pacific, is usually propagated by means of cuttings from the stem, each with a pair of leaves attached. It grows best in a warm somewhat sandy soil and is an important food plant in Polynesia; it was formerly a staple food for the Maori in the north of New Zealand.

Lantana camara (Fig. 61). This is a pretty, spreading bush, about 3 ft high, with clusters of small yellow, orange, pink or white flowers. Originally a native of tropical America, it was introduced into the Pacific as a garden plant, and, as in Malaya, it has spread rapidly and become in places a serious pest.

Metrosideros (Hawaiian name, *lehua, ohia*).

The various kinds of *rata* and the 'Christmas tree' of New Zealand belong to this genus. *M. polymorpha* is the commonest of several species found in the Pacific islands. It is an exceedingly variable plant, ranging in

size from a small creeper a few inches long to a massive forest tree 100 ft. high. The tuft of crimson stamens in the flower is characteristic, but the size and shape of the leathery leaves is very variable. As a tree it is an important constituent of rain forest in most of the Pacific islands, especially in the Hawaiian group.

Morinda citrifolia (Tahitian name, *nono*; Pukapuka, Niue, *nonu*; Hawaiian, *noni*; Fijian, *kura*).

This is a straggling shrub or small tree on coral islands and sea beaches. It is known by its very large glossy leaves in opposite pairs, four-sided twigs, and the curious greenish fruit, rather like an unripe strawberry in appearance, with a pungent smell. The pulp of the fruit was formerly eaten in Tahiti, after being passed through water. In Tahiti, the leaves are used to give a flavour to fish in cooking, and also medicinally, to reduce inflammation. In Fiji, the young shoots of the plant give a basic medicinal oil, for use in ringworm and other diseases. But the most important use of the plant in most parts of the Pacific is for dye; the roots give a yellow dye, and the bark a red one.

Musa (banana, plantain; Tahitian name, *mei'a* for the cultivated varieties and *fe'i* for the wild mountain varieties; known generally in western Polynesia as *futi*; Mangaian name, *koka*; Fijian, *vudi*; Trobrionds, *usi*; Blanche bay, *wudu*).

There are many varieties of the banana recognized by the natives. Some are known to be of recent introduction, others are long established, but possibly none—not even the wild varieties—are truly native to the Pacific. They vary considerably in the size, length, shape and colour of the fruit, which is one of the staple Pacific island foods. The leaves are commonly used as wrappings for food and small articles.

Palms.

Palms, both wild and cultivated, are a conspicuous feature of the landscape, especially on small islands or in coastal districts. The most widespread is *Cocos nucifera* (coconut; general Polynesian name, *niu*; Trobriands, *nuya*; Blanche bay, *lama*) the most important economic plant of the Pacific. Its original home is uncertain, some views inclining to tropical America, others to south-east Asia as the source. Though coconut palms are found on almost every island large enough to support any land plants, they are probably not native there, and have nearly always been planted. Coconuts are often carried long distances by sea, but rarely succeed in establishing themselves on the shore without assistance. The liquid in the nut is used as a drink, sometimes taking the place of water, and the flesh of the nut is used at different stages for food, as well as providing copra, one of the basic Pacific export articles. The shell of the nut provides drinking vessels, spoons, ornaments and fuel; from the husk is made a kind of sennit cord. The leaves are used as thatch for houses and, when dry, as torches; the leaflets are plaited into baskets, fans, eye-shades, mats and wall-screens. The dry spathes are used for fuel, and the fibrous material which covers the base of the fronds where they are attached to the trunk is used as straining-cloth and for bags. The trunk is utilized as timber, and there are a number of other uses to which parts of the palm are put.

Other important palms, especially in the Western Pacific, are: the areca, which provides the nut commonly used in betel-chewing; the sago, from the trunk of which a flour is extracted; and the nipa, which like the sago grows in swamps, and also like it provides leaves which are used as thatch.

The indigenous palms of the Pacific are almost all endemics of a single

island or group ; Lord Howe island, for instance, has no less than four species not found elsewhere.

Pandanus (Plates 52, 55). European name, screw pine ; Polynesian name, *hala*, *fara* and other variants, with *kiekie* for some species ; Trobriands, *kayburiburi* ; Blanche bay, *waum*, *marita*).

The many species of pandanus, though called screw pines from the twisted arrangement of the leaves, are not in any way related to the true pines. They are all shrubs or trees with narrow saw-edged leaves and slender branched trunks supported on a mass of straight stilt roots. The fruit somewhat resembles a pineapple in appearance, but is formed of many separate hard segments. Species of pandanus are very numerous on both the 'high' and the 'low' islands and are often abundant enough to form a striking feature of the landscape. One of the most widespread species is *P. tectorius*. The pandanus plays a very important part in native life, providing the people with mats, thatch, screens and sometimes clothing from the leaves ; scent from the male inflorescence and various types of food from the fruit, which is rich in starch and glucose. On many of the low coral islands, where other cultivated plants can be grown only with difficulty, the pandanus fruit is an important part of the diet.

Pisonia grandis (=*P. inermis*. A common Polynesian name is *puka*).

This is a tree varying in height from about 15 to 80 ft. and forming woods or groves on coral islands and other dry places. The leaves are thin, elliptical and oblong, arranged in opposite pairs, and about 3–6 in. long and 1 to 3 in. wide. The fruits exude a gum which is used as a bird-lime in Hawaii. The trunk is thick, but the wood is soft and not greatly used, except for canoe floats.

Pemphis acidula (sometimes known as ironwood).

This is a bush, occasionally as much as 20 ft. high, which often covers large areas on coral islands. It provides good firewood and the very hard wood is used by the natives for carving and formerly for weapons. The main trunk is stocky, the branches gnarled and twisted, bearing small white flowers and tiny silky grey leaves. It has rather the appearance of an overgrown heath.

Scaevola frutescens (=*S. Koenigii*. Sea-lettuce tree).

This is one of the commonest bushes of the seashore, often covering large areas on coral islands. The leaves are from about 3 to 10 in. long, light green and fleshy, tapering gradually backwards to the stalk. The flowers (Fig. 53) are white or pale lilac, tinged with yellow. The berries, white when ripe, are crowned with the remains of sepals, like an apple. Other species of *Scaevola* grow inland in Samoa, Hawaii and other large islands.

Spondias dulcis (=*S. cytherea*. Often known to Europeans as vi-apple; Tahitian and Cook islands name, *vi*).

The tree is large and spreading, from 40 to 50 ft. high, and is one of the few deciduous trees of the tropical Pacific. The leaf is pinnate, with a terminal leaflet. The flowers are small and whitish. The fruit, which hangs in clusters, is like a medium-sized apple, smooth-skinned and of a rich golden colour when ripe. The skin is leathery and the flesh is aromatic and of an agreeable flavour, slightly acid. The fruit is regarded as a delicacy. It has a large spiked core, with several pear-shaped seeds. The wood of the tree is soft and of little value as timber.

Terminalia catappa (Fig. 57). Tahitian name *autara'a* ; Fijian *tavola*.

This tree is commonly planted by roadsides throughout the tropics and

Plate 53. Norfolk island pines (*Araucaria excelsa*), Norfolk island

Plate 54. The papaya or pawpaw (*Carica papaya*)
A commonly cultivated tree of the Pacific. The short unbranched trunk and large divided leaves give it a characteristic appearance. The fleshy fruits may be seen below the lower leaves.

Plate 55. *Pandanus mei*, Hivaoa, Marquesas
This species is endemic to the island.

grows wild on sandy beaches in the Western Pacific. It can be recognized by the stiff outstanding branches arranged in tiers, and the broad oval leaves which are borne in rosettes and turn red before falling. It resembles *Barringtonia*, but has less pointed leaves, and its flowers are quite different. The fruit is edible and the wood, which is close-grained and variegated with shades of brown, is used in Tahiti by cabinet-makers and in Fiji for gongs. In Fiji also the leaves are used medicinally.

Thespesia populnea (Tahitian name, *miro, amae*; Hawaiian, *milo*; Easter island, *makoi*).

This is very like *Hibiscus tiliaceus*, but it is a tree rather than a shrub, and the leaves are more triangular, with longer points—like those of the black poplar rather than those of the lime. Moreover, they are not hairy beneath. The tree grows chiefly on sandy shores. Its handsome dark wood is used for carving, and in some islands poles of it are used as rods in bonito fishing.

Tournefortia (*Messerschmidia*) *argentea* (European name, tree heliotrope; Tahitian name, *tahinu*; Pukapuka, *taeyinu*; Gilbert islands, *ron*; Fijian *evu*, also *roronimbembe* and *kauniyalewa*, the second name meaning 'butterfly's rest', and the third referring to the use of the plant medicinally for women's complaints).

This is a tree of dry sandy ground near the sea, and is often the only tree on small coral islands. The leaves (Fig. 54) are narrowly elliptical, and are conspicuous for their thick covering of silky hairs. The flowers are mauve and are similar to those of the true heliotrope, to which the tree is related.

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'Floras'

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Chapter VI

FORESTRY

Destruction of Forests : Present Situation : Bibliographical Note

Forests are necessary to human prosperity for several reasons. In the Pacific islands they are a source of food and other materials, such as timber and fuel, and they play a part of equal or greater importance in conserving and regulating water supplies. In rugged mountainous country subject to heavy rainfall, such as the 'high' islands of the Pacific, their value in protecting the soil against erosion can hardly be over-estimated.

Over by far the greater part of the land area of the Pacific, forest is the natural climax vegetation. Except on the smaller coral islands, which are, and always have been, poorly provided with large trees, climate and soil are everywhere suitable for trees to grow; until quite recent times a large percentage of the surface was in fact forest-covered. The forests are mainly evergreen rain forests, consisting mostly of slow-growing hardwoods forming mixed stands with no single dominant species. The Western Pacific islands, particularly New Guinea, New Caledonia and the Fiji group are, however, fortunate, and indeed almost unique among tropical countries, in possessing also forests rich in conifers, such as the kauri and the hoop pine, which yield softwoods. Because they are easily worked and even in grain, these coniferous timbers are used in far greater quantities by modern communities than are the generally more durable hardwoods.

Destruction of Forests

Though forests at one time covered so large a part of the land area, the Pacific islands, far from being one of the world's great timber-producing areas, are today for the most part not even self-supporting in timber. In many islands soil and water supplies have suffered gravely, or are now menaced, by the destruction of the forests. Except in New Guinea and some of the neighbouring groups of islands where the population is still sparse and primitive, the present area of forest is everywhere inadequate to meet the needs of the inhabitants and to safeguard the prosperity of agriculture. The chief

aims of forestry in the Pacific, as in most other parts of the world, must be to preserve the forests that remain and to increase their area by reafforestation and the planting of denuded land.

The destruction of the forests is only partly due to the felling of trees for timber and the clearing of forest land for agriculture. In most parts of the Pacific large areas have been deforested by semi-wild domestic animals, such as pigs and sheep, which eat the tree seedlings and prevent the forests from regenerating. Some idea of the magnitude of this problem will be given when it is stated that in the Territory of Hawaii, which has the longest established and most highly organized forestry service in the Pacific, 22,364 goats, 6,483 sheep, 4,887 pigs and 497 cattle, as well as a few horses and donkeys, were killed in forest reserves in the years 1928–30.

Though the coming of the European and his domestic animals has accelerated forest destruction greatly, the process was begun much earlier by the native inhabitants. Already at the time of their discovery by Europeans, many of the less heavily wooded islands had been practically denuded of trees, so that timber had become a highly prized commodity. Easter island, for instance, which is believed by botanists to have been wooded at the time of its first colonization, soon became almost treeless. When Du Petit-Thouars visited it in 1836–39 the natives were far more eager for wood than for scissors or knives. The wood hunger of the Easter islanders still persists, and every piece of wood coming to the island is carefully preserved. The rapid depletion of the timber on many islands soon led to the export of timber from the better-wooded islands. Fiji, still today better provided with forests than most of the neighbouring groups, in pre-European times exported logs to Samoa and Tonga for making war canoes. To some extent the meagre timber supplies could be supplemented with driftwood; some of the most famous of the ancient Hawaiian war canoes were made of Douglas fir which had drifted across the sea from western North America.

Sandalwood

The first Pacific timber to play a part in European trade was sandalwood, obtained from several species of small trees belonging to the genus *Santalum*, native in the open forests of the dry zones of Hawaii, Fiji, New Guinea and other islands. Sandalwood is one of the world's most expensive timbers, as the heartwood yields a fragrant oil and is itself in great demand, particularly among the Chinese, who use it in religious ceremonies. Sandalwood trees

were never very plentiful and the supply soon became exhausted. (For the sandalwood trade see pp. 269–71, 291–2.) In Fiji, the *yasi* or Fijian sandalwood (*Santalum yasi*) was at one time fairly abundant in the Mbua province of Vanua Levu, but even by 1816 it was becoming scarce. In 1929–30, 50 tons were exported from Tholo West, after many years during which the sandalwood trade seemed to have disappeared for ever. The tree was by then all but completely exterminated and in 1930 the government took the long-overdue step of prohibiting the export. The history of sandalwood in Hawaii is very similar but forest reserves have been created in which the tree has increased in abundance very satisfactorily, and before long it may again become an article of export. The native Hawaiian *Santalum Freycinetianum* has been supplemented by planting the Indian *S. album*, which grows faster and seems well suited to the soil and climate. Sandalwood was once one of the most important exports of Papua, fetching as much as £40 per ton; but though the supply is by no means exhausted most of the trees remaining are in the savannah and gully forests some distance from the coast, and are therefore comparatively inaccessible. Small amounts of sandalwood are still left in the New Hebrides and New Caledonia.

Beginnings of Conservation

Throughout the nineteenth century and the first quarter of the present one the story of the Pacific forests was one of wasteful exploitation and destruction by natives and Europeans alike. Timber was recklessly felled without any thought of replanting or maintaining a steady supply. Forests were destroyed at an ever-increasing rate by clearing, shifting cultivation, and the ravages of domestic animals. Only very recently has it begun to be realized that the protection of forests is economically vital, not merely in order that the islands may become self-supporting in timber, which in the future may not be so easily obtainable from abroad, but to provide for the conservation of the soil and water necessary for agriculture. The first administration to become alive to the dangers of deforestation was that of the Territory of Hawaii, where the sugar planters have long realized the necessity of forests as the collectors and conservers of the rain water used for irrigating the cane fields. An efficient forestry department has been active here for many years, the first forest reserve being established in 1904. Other areas have been

slow to follow suit; in Fiji a forestry department was not created till 1937, and in the Territory of New Guinea not till 1938.

Present Situation

The present position of forestry in the Pacific is so different in different areas that they must be dealt with separately.

Hawaii

In the Territory of Hawaii the total forest area is 1,100,000 acres, of which 275,000 acres are in accessible situations. This is equivalent to rather more than a quarter of the land area, or 2·6 acres of forest per head of population. There are no native conifers or softwoods of any kind; the natural forests consist of slow-growing hardwoods, of which the most useful are the *koa* (*Acacia koa*) and the *ohia lehua* (*Metrosideros polymorpha*). Both of these produce timbers which can be used for making furniture, ukuleles, veneers for radio cabinets, flooring, etc., but are not suitable for large-scale constructional work. Redwood and Douglas fir can be imported cheaply by schooner from the United States for building purposes, and it is considered more economical to do so than to attempt to produce softwoods locally. The *algaroba* (*Prosopis juliflora*), introduced into Hawaii in 1828, has been spread by animals and now covers over 100,000 acres, chiefly in the dry lowlands. This tree is the chief source of firewood, and large quantities are used particularly by the United States Army.

Because of the limited usefulness of the native timbers and the mountainous nature of the country, forest policy in Hawaii aims primarily at conserving and regulating the run-off of water, and not at timber production. About 10,000 board-feet of *koa* wood are cut yearly, and small quantities of this and other native hardwoods are used locally. A very small amount of timber is exported to the United States. In the government-owned forests, which form 65% of the total reserved area, no timber at all is cut.

The main work of the forest administration consists of reserving and protecting the existing forests and replanting treeless land, particularly on watersheds. In 1931 there were 63 forest reserves on the five largest islands, varying in size from 10 to 122,782 acres, the total reserved area amounting to 1,021,314 acres. Reserves not belonging to the government are mostly owned by sugar plantation companies and large estates. The actual field work of the forest

service consists mainly of fencing, destroying harmful animals such as goats and sheep, and planting denuded areas. The chief species planted are introduced trees such as American white ash, and eucalyptus and various other trees, many of them imported from India and Australia. These foreign trees grow faster than the native species and seem well suited to Hawaiian conditions. There is no unfavourable season for planting, so it can be carried on all the year round. The seedlings are raised in flats and pricked out into boxes or rejected cans, which can be obtained free of charge from the pineapple canneries; the soil used is carefully sterilized to kill pests. The young trees must be planted out with their ball of earth, as trees planted in the usual way with bare roots do not survive the drying winds and scorching sun. Special attention is given to gulleys and other ground bared by erosion; the Australian tree *Casuarina glauca* is particularly useful on such land. Some burned or otherwise denuded areas have been successfully afforested by scattering tree seed from aeroplanes. Apart from wild animals, one of the main enemies of the forests is the *uluhi* (staghorn fern, *Gleichenia linearis*), which, as in other parts of the Pacific, forms dense thickets which spread very rapidly. In droughts these thickets become so dry that they catch fire very easily; they also tend to invade the forest, smother the young trees and prevent regeneration. No successful way of controlling this pest has yet been found.

The forest administration consists of the territorial forester with four trained assistants, one to each of the main islands. In addition, there are 18 forest rangers and 64 men engaged in tree planting and tending the nurseries (1931 figures). The cost of the work is met by appropriations made by the local legislature and by a grant of $2,000,000 from the federal government under the Clarke-McNary law.

New Guinea

Conditions in New Guinea make the sharpest possible contrast with those in Hawaii. Here the greater part of the land is forest-covered; the population is relatively very sparse and problems such as erosion and water conservation are not yet urgent. The forest can therefore be regarded mainly as a source of timber, for both local use and export. The forests are mainly mixtures of many species of hardwoods, some of them, such as the *taun* (*Pometia pinnata*) and the 'New Guinea walnut' (*Dracontomelum mangiferum*),

of fairly good quality. The best hardwoods, for instance, the *kamarere* (*Eucalyptus deglupta*) of New Britain, and *Afzelia bijuga*, occur too locally or in too small quantity to be exploited economically. One timber tree, the *erima* or *ilimo* (*Octomeles sumatrana*), which produces a light-coloured, light-weight plywood of fairly general utility, is exceptional in being social, sometimes growing in nearly pure stands. Besides these broad-leaved trees, New Guinea possesses fairly large quantities of valuable coniferous softwoods, of which the best are the two kinds of hoop pine, *Araucaria Cunninghamii* and *A. Klinkii*. These conifers are found in the mountains, generally above 4,000 ft., and are therefore often difficult or impossible to exploit. In some places, however, they have provided a large amount of timber for local use—for instance in the Wau goldfield, where several small towns have been built largely of *Araucaria* timber taken from the neighbouring forests and sawn up by machinery imported by air.

The export of timber from New Guinea is handicapped by the scattered and often inaccessible supplies, by the distance of suitable markets, and by the proximity of Australia, which produces some of the world's best hardwoods. In recent years, however, the depletion of home-grown supplies has led Australian sawmillers to look further afield for supplies, and this has led to the establishment of a number of sawmills in the coastal areas of New Guinea. Timber exports from the Territory of New Guinea, which in 1933–34 were valued at only £180, rose in 1937–39 to £6,030 of logs (equivalent to 3,103,996 superficial ft.) and £480 of sawn timber.

In 1925 a lengthy report was issued on a survey of the forests of Papua and the Territory of New Guinea by C. E. Lane-Poole, Inspector-General of Forests in the Commonwealth of Australia. One of the recommendations of this report was that a staff of qualified foresters should be set up. This recommendation was not carried out till 1938, when two Australian graduates were appointed. The most important duty of these officers, apart from exploration and detailed survey of the forests, has been to control exploitation by a system of licensing and to introduce a regular inspection of logs intended for export—the reputation of New Guinea timber having suffered in the past because logs badly infested with borers had been placed on the Australian market. At the end of 1938, nine sawmills were operating in the Territory of New Guinea and about 60,000 acres of government land were held under permit to cut and remove timber.

Fiji

In the Fiji islands the present condition of forestry is to some extent intermediate between conditions in New Guinea and those in the Hawaiian islands as, though there is a fairly dense population there are still considerable areas of forest in accessible situations. These forests are of considerable economic value for supplying timber for local consumption, as well as for maintaining water supplies and protecting mountain slopes against erosion. The total area of the forests is 2,366,000 acres, of which 2,317,000 acres are rain forest and 48,900 acres are mangrove forest. The rain forest consists mostly of hardwoods, none of which are of outstanding commercial value. But in some places there are large quantities of valuable coniferous woods, notably kauri (*Agathis vitiensis*) and *ndakua salusalu* (*Podocarpus vitiensis*)—both useful softwoods for a variety of purposes—as well as *yaka* (*Dacrydium elatum*)—an excellent wood for high-class furniture and similar purposes. *Kauvula* (*Endospermum sp.*) is used locally on a large scale for making cases for bananas, pineapples and vegetables. The sandalwood in the forests of the dry zones has already been mentioned. The mangrove forests of the Rewa delta and Navua are the chief source of fuel in the islands for both domestic and industrial purposes.

Until very recently timber was felled with little restraint by both natives and Europeans ; there was no attempt to maintain a sustained yield or to reafforest denuded areas. The Fijian Kauri Timber and Land Company held a concession to cut timber (chiefly kauri and *ndakua salusalu*) at Nandarivatu in the mountains of Viti Levu. Another concession was held by Pacific Timbers, Ltd., covering 225,000 acres in Vanua Levu, from which nearly all the *yaka* cut in Fiji was obtained. The mangrove forests which, unlike the inland rain forests, belong to the Crown and not to the natives, were exploited under licence in a very wasteful manner, chiefly by Fijians at Rewa and Punjabis at Navua. In addition, Fijians were allowed to take forest produce from the mangrove forests for their own domestic use, but not for sale. In spite of the large amount of native timber available, about two-thirds of the timber consumed in Fiji was imported from Canada. A common complaint was that, though local timber was durable, it was not available in sufficient quantities at the right time.

In 1930–32, R. A. Sykes was seconded from the Nigerian Forestry Department to survey the Fijian forests and draft a forest policy. In this report it was pointed out that the consumption of the best

native timbers greatly exceeded the rate of replacement; unless steps were taken to limit exploitation and replant the forests the useful timber would soon be exhausted. A detailed forest policy for five years in the first instance was suggested, the total cost of which would be £12,500. It was hoped that this would ensure a sustained yield of timber and eventually make the islands self-supporting in timber. The proposed forestry department was not in fact set up till 1937.

Other Areas

Apart from Hawaii, New Guinea and Fiji there is little to note on forestry in the Pacific. Elsewhere, except in New Caledonia, there is practically no organized exploitation of timber, though the kauri concession on Vanikoro should be mentioned. It is evident that the only part of the Pacific which has any prospect of establishing itself as an area exporting timber on a large scale is New Guinea and the neighbouring islands. Even there the nature and distribution of the native timbers make it unlikely that timber exports will ever be very large. For most of the Pacific, as in Hawaii, the function of the forests must be mainly to protect water supplies and soil; most islands can hardly hope to become even self-supporting in timber. Though the Pacific forests are not important as timber producers, they are none the less necessary to local prosperity, and it is to be hoped that rational plans for reservation and reafforestation will soon be put into effect.

BIBLIOGRAPHICAL NOTE

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Chapter VII

FAUNA OF THE PACIFIC OCEAN AND ITS ISLANDS

Characteristics of Island Fauna : Changes produced by Man : Distribution of Pacific Land Fauna (Birds) : Life in the Ocean : Pelagic Animals : Animals of the Sea Floor : Animals of the Abyssal Depths : Colour and Phosphorescence : Types of Corals : Growth of Coral Colonies : Animals Associated with Coral Reefs : Mangrove Associations : Effects of Seasonal Changes on Pacific Fauna : Fauna of Economic Value to Man : Bibliographical Note

The animals of the Pacific area are to be found in such a vast range of habitats, from the tree tops of island forests to the ooze at the bottom of the ocean deeps, that it would be quite impossible to give even a brief description here of more than an insignificant fraction of the many very different kinds. All that will be attempted is a general account of the relationships of the animals to their surroundings and to one another in the most important of their many diverse environments. Works giving more detailed descriptions of particular animals are cited in the Bibliographical Note on p. 211.

Characteristics of Island Fauna

The special character of insular faunas rests on the conditions common to all islands—isolation, space restriction, and special insular climates. The fauna found on an island depends particularly on the distance from the nearest continental land mass, and on the length of time since connection with that land existed, if ever; as well as on such environmental factors as climate and type of vegetation. From a faunistic point of view, islands may be divided into two distinct types, continental and oceanic islands. A continental island has at some time been part of the mainland, and if not too small will contain the same fauna as the land from which it was separated. Ancient continental islands of any size will lack some groups, which have become extinct on the island, or which have evolved on the mainland since the separation took place. On the other hand, primitive forms which have become extinct on the mainland owing to competition with more modern species may survive on islands. An oceanic island is one that has never been attached to a continent, but has been formed independently in mid-ocean by volcanic agency or by the building up of a coral reef. Such an island must originally have been without air-breathing

animals and its land fauna will consist of animals which have been able to cross the ocean by flying, swimming or by some passive means. Animals which are incapable of flight or other aerial transport, or to which sea water is fatal at all stages of life history, are excluded from oceanic islands. Amphibia and many other fresh-water animals seem to be excluded from oceanic islands for these reasons.

Many different kinds of animals are able to reach islands by air. Small forms like weak-flying insects and newly hatched spiders on gossamer threads may be carried to considerable heights by ascending currents of air over land, and before they come down again they may drift for great distances; there is an anti-trade-wind current of air at no great altitude over the Pacific and many small forms may have been carried eastwards by it. The distribution of the fauna of the Pacific islands shows that most forms have arrived from the west, and therefore against the prevailing winds. Birds and more strongly flying insects will be able to fly less aimlessly, and many of them show a tendency to fly against a weak wind. The more strongly flying birds and bats will generally avoid being blown out to sea; but if they are blown out of sight of land by a strong wind the strongest fliers will go furthest before they perish, and will stand a better chance of reaching an island. Finally, we come to birds like the Pacific golden plover and the long-tailed cuckoo, which have such powerful flight and such a wonderfully developed sense of direction that they are able to fly deliberately from the mainland to the furthest islands and back again each year.

Other animals are carried to islands by sea, some by active swimming. There is the example of the Solomon islands' crocodile which came ashore in Fiji and killed several people before it was destroyed. Many small animals are carried about on driftwood. Weevils must often be carried about the oceans in this way, as their larvae frequently live in wood, and this may explain their predominance on many islands; in the Marianas, for example there are more weevils than all other species of beetles put together. Lizards, especially skinks, are widespread in the Pacific islands, but land mammals seem not to be able to survive long on driftwood and are mostly missing. Why snakes are not more widespread than they are is rather puzzling. A boa constrictor was carried 200 miles on a floating cedar tree to St Vincent island in the West Indies, and boas range from New Guinea through the Bismarck archipelago, the Solomons, and the New Hebrides to Fiji and Samoa. Other

snakes are found in New Caledonia and in the Society islands. The sea snakes are naturally much more widely distributed. It should be noted, however, that the normal currents of the tropical Pacific (Figs. 120–1) flow in the opposite direction to that required to account for the distribution of the fauna. Logs from north-west America are washed up on the Hawaiian shores and fish-net floats from Japanese waters also reach these islands. Bottles thrown into the sea off the Central American coast drift right across the Pacific and are collected on the Philippines, the Solomons, or anywhere between these tracks. These are the normal currents today. What currents may flow as a result of cyclonic disturbances or other abnormal conditions, and what the currents may have been in the past, is not known. American elements are absent from the fauna of the Pacific islands other than the Galápagos, Juan Fernández, and islands near the American coast. Probably the distance is too great and the drift too slow.

The islands west of a line drawn from the Bismarck archipelago and the Solomons through the New Hebrides, Fiji and Tonga to the Kermadecs and New Zealand, including the islands named, have a fauna which is clearly the remnant of a continental fauna. The islands to the east of this line are either volcanic like Samoa, or atolls of coral limestone like the Ellice islands, and the ocean is continuously deep here. Fossil-bearing strata are absent from these islands and geologists are not all agreed as to whether there ever was a land mass in the centre of the Pacific or not; but it seems incontestible that the present fauna of these islands is oceanic, and most zoologists are agreed that if there ever was a central continent it must have sunk completely and that neither the present islands nor their flora and fauna are a remnant of a continental mass.

The distribution of the land molluscs of the Pacific islands is interesting in this connection and rather different from that of most groups of animals. Throughout Polynesia (including the Hawaiian islands) the snail fauna is very uniform and at the same time very different from that found elsewhere. The ancient generalized genus *Partula* is confined to Melanesia and Polynesia, but is widely distributed throughout these island groups. On the other hand, many groups which are widely dispersed in the rest of the world, including other oceanic islands—for instance, the Helicidae and Arionidae—are absent. The distribution of the land molluscs is thus consistent with the hypothesis of an ancient continental land mass uniting all Polynesia with Hawaii, and it has been suggested

that the land broke up into smaller land areas in middle Mesozoic times—that is, early enough to account for the absence of mammals and other animals in the area (see Table of the Main Geological Periods, p. 15).

The presence of amphibia in the Bismarck archipelago, the Solomons, and Fiji is very good evidence that these islands are of continental origin. Amphibia, like many other freshwater animals, are unable to survive exposure to salt water and have special difficulty in reaching islands; they are often poorly represented even on undoubtedly continental islands since they are easily liable to extinction and cannot readily be replaced. There is practically no standing fresh water in the way of pools or ponds on small islands, and heavy rains and steep hills combine to form torrents which would wash away the tadpoles of ordinary amphibia rather than allow their leisurely development. The amphibia of Melanesia are able to survive under these conditions because they have dispensed with a free-swimming tadpole stage. The evolution of these special methods of reproduction can only have proceeded gradually, and must have taken place while the islands were separating off from the mainland and getting smaller.

Freshwater molluscs are very rare and aquatic insects are absent on most of the small islands. Some of the older oceanic islands have freshwater snails which have evolved from marine forms. The Hawaiian islands have few aquatic insects, no caddis flies, only four species of water beetle, and two aquatic *Hemiptera*. Dragonflies with their great powers of flight are, however, widespread on islands. Most of the few freshwater fishes found on oceanic islands have originated from the sea, and the same is true of the prawns found in island streams.

Island species are isolated from their fellows on the mainland or other islands and tend to evolve along independent lines. The more effectively and the longer an island has been separated from the nearest inhabited area the more endemic species it will have; but the accessibility of a particular island from other more thickly populated areas will differ for the different groups of animals. If an archipelago is compared with a neighbouring mainland it is evident that the isolation of the separate islands has led to the evolution of many separate species, many of which are confined to single islands. The Philippines, for example, have over 1,000 species of land snail, while there are only about 600 in the whole of Indo-China and Siam. The amphibia of the Solomon islands,

which are Papuan and not Australian in origin, are fairly homogeneous and species which are found in the Solomons are not found in New Britain and New Ireland. This indicates that for a long period the Solomons were contiguous with one another.

On ancient islands well isolated from the continent the genera are often split up into many species. The Hawaiian islands—very ancient volcanic islands 2,000 miles from the nearest land—have a very high proportion of endemic species of land snails, birds, insects and fish. There is a primitive family of land snails represented by fourteen genera, and a great many species—of which none, either living or fossil, are found anywhere else. Some of the genera are confined to single islands and each of the valleys radiating down from the mountains is often characterized by its own series of species. The weevil-like genus *Proterhinus* has evolved on the Hawaiian archipelago and there are about 150 species endemic to these islands. A few species have spread out from there, one has been found in Samoa, one in the Phoenix islands and two in the Marquesas; but none is known elsewhere.

The Galápagos islands are not so completely isolated and two ocean currents flow past them, one (in their winter) from the coast of Peru, and the other (in their summer) from the Gulf of Panama. The 46 species of land snail, whose dispersal may have been favoured by these currents, are mostly endemic, but they all belong to Central or South American genera. The same picture is given by the rest of the Galápagos fauna.

Isolation on islands affords effective protection against the entrance of competitors, and forms which have succumbed in the struggle with more advanced species on the continent may survive on islands. Moreover, the absence of native land mammals other than bats on most islands is specially favourable for bird life. The rather helpless pigeons increase in numbers from the Malay archipelago eastwards as the mammals decrease, and are strikingly developed in Polynesia, where no native land mammals exist (apart from bats). The distinctive Didunculidae family of pigeons is confined to two islands of Samoa.

The absence of predators makes it possible for island birds to develop unusual colours. The evolution of the birds of paradise in New Guinea and the immediately adjacent islands may be explained in part in this way. (The New Guinea land fauna is described in vol. IV, pp. 115–9.) For the same reason a number of island birds are flightless. Flightlessness in birds and insects on islands is, however, characteristic especially of small level islands in stormy areas. The

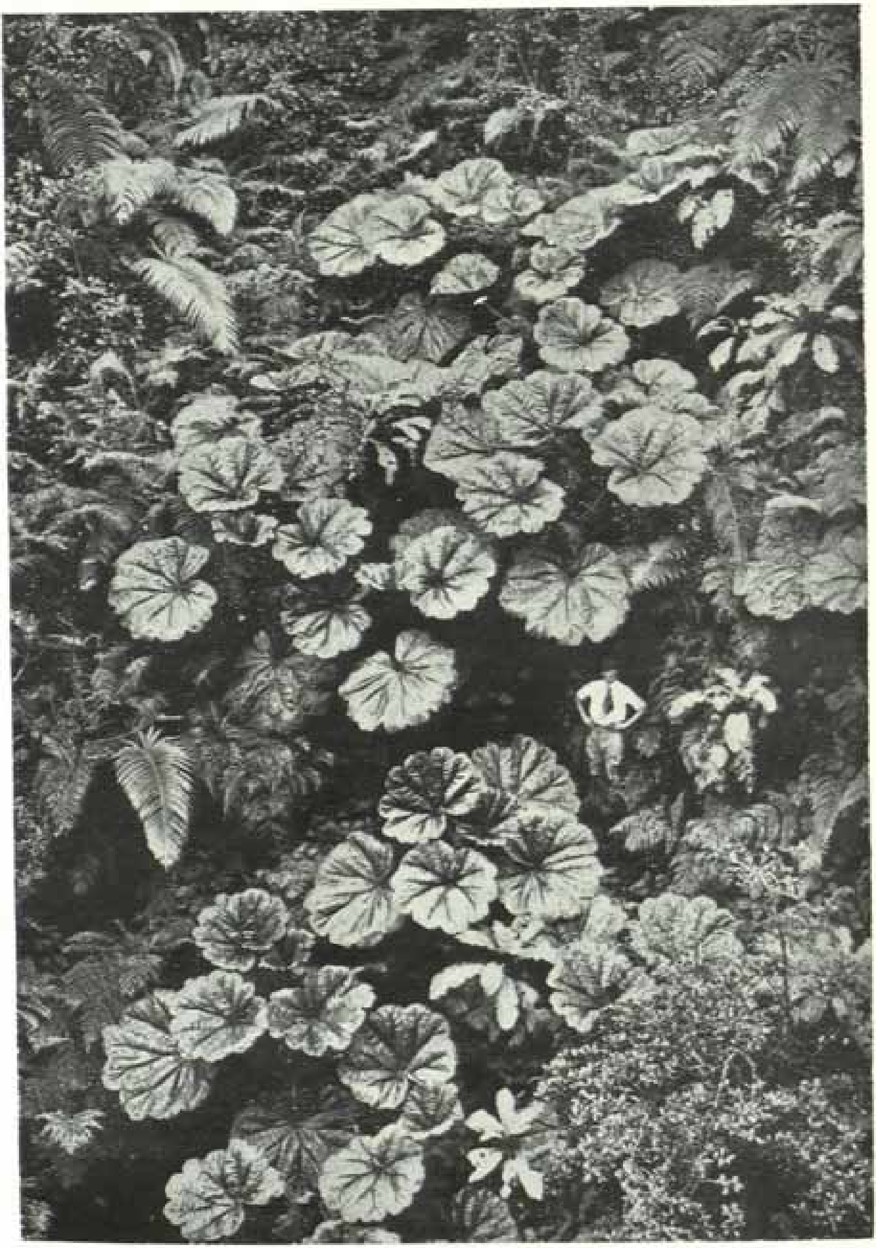


Plate 56. A valley in the mountains of Hawaii
The vegetation is luxuriant and includes many ferns. The large leaves belong to a species of *Gunnera*.

Plate 57. Racing crabs (*Ocypoda*), Gilbert islands

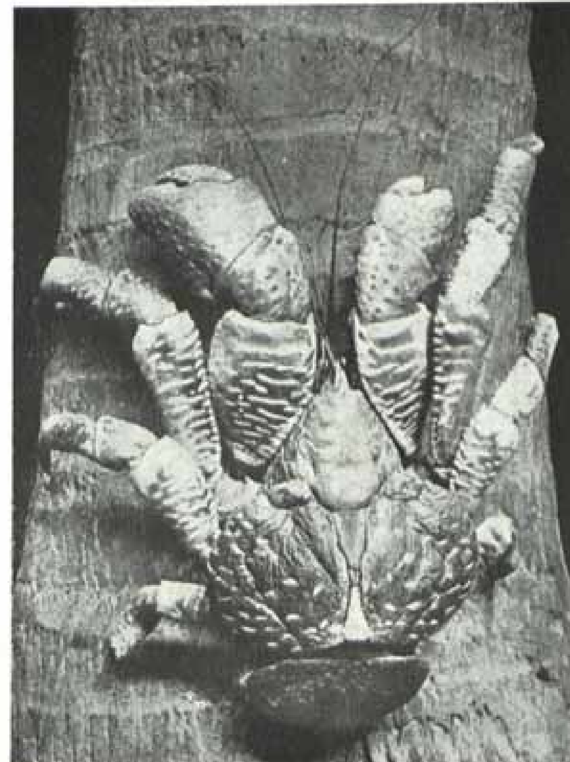


Plate 58. Coconut crab (*Birgus latro*)
The crab is shown climbing a palm trunk. This species is said to be able to split open the nuts to extract the kernel.

most striking examples are found in the Kerguelen, Crozet, and other sub-antarctic islands, and the phenomenon is not quite so conspicuous in the Pacific.

The size of island animals frequently differs from that of their mainland relatives. Reptiles, especially tortoises and lizards, tend to be very large. The largest living land tortoises are found in the Galápagos, which also have two large species of iguana. These may well be relics of faunas which were originally more widely distributed; but the large geckos and skinks of, for example, New Caledonia, suggest a real connection between insularity and large size. On the other hand, many mammals become smaller when confined to islands.

The constant humidity of islands, together with their relatively long coast line, favours the land crustaceans. Small tropical islands have great numbers of land crabs—hermit crabs, racing crabs and coconut crabs (Plates 57, 58). The hermit crabs adopt the shells of land snails in the Solomons and other islands. All land crabs migrate to the sea to breed and their larvae live in the surface waters and are carried from island to island by ocean currents. Most of the species are, for this reason, widespread in the Pacific islands.

Changes Produced by Man

The absence of native predators and the lack of competition with modern species, while it has permitted primitive species to survive on islands and has allowed the development of lax habits and bizarre forms which would otherwise have succumbed in the struggle for existence, at the same time renders island species especially liable to extermination by introduced forms. An ant introduced into Hawaii has destroyed the endemic forms in extensive forest areas. The introduction of cats and dogs, which have run wild, has resulted in the extermination of the native fauna of several islands—though very occasionally the animals have been able to change their habits in time, like the tooth-billed pigeon of Samoa, which has recently adopted an arboreal life. Lord Howe island was made a bird reservation in 1879, but in 1918 a steamer was wrecked there and its rats swam ashore and multiplied; within three or four years most of the native fauna had been exterminated. Until recent years native birds were plentiful in Viti Levu, the largest island of Fiji. Then minahs and bulbuls were introduced from India, and also the mongoose, the last for the purpose of killing the rats in the plantations. The result has been that these adaptable immigrants, especially the

mongoose, have driven all native birds and most of the other small native fauna into the remoter recesses of the island. Native birds are rarely seen, while minahs and bulbuls are abundant, even in Suva.

Many kinds of animals have been introduced to the island by man, either deliberately or unintentionally, first by the native peoples and more recently by Europeans. The Melanesians and Polynesians coming from the west brought with them domesticated dogs and pigs, as well as many cultivated plants. With them came the rat *Rattus exulans*, the only wild mammal other than bats to be found in any of the islands east of the more westerly Solomon islands. This small rat has evidently been carried about in canoes, and is found n nearly all parts of Oceania, southwards to New Zealand, eastwards to Tahiti and northwards to the Hawaiian islands. Such introduced animals often spread with great rapidity in their new home. A few rabbits left on Phoenix island in 1889 seem to have been so prolific that, it is said, the island was over-run with them some years later. Deer, introduced into New Caledonia from the East Indies, multiplied so greatly that they became a pest by reason of their damage to crops; about 1930, settlers in a southern district organized a drive in which machine guns were used to kill them.

Domestic animals have often escaped and their descendants become feral. The goats of the Galápagos are much more difficult to approach than are most of the native animals which, owing to their long freedom from interference from predators or human beings, are astonishingly tame.

Pigs had run wild in many islands before Europeans arrived and wild cattle, which owe their existence to Europeans, are found in the Marquesas, and in Samoa and in Fiji. (The internal and external parasites of pigs and men are of Asiatic origin; but there are some rather surprising absences. The relative absence of tapeworms and of *Trichinella spiralis* (p. 231) from a human population intimately associated with pigs and rats is quite unexplained, and so is the absence of *Ascaris lumbricoides* in some areas, though where it has been introduced it has rapidly become common.)

Man, besides introducing species by active or passive means, also has a profound effect on the environment, sometimes enabling a species arriving by independent means to survive where it would otherwise have lacked subsistence. Many insects are restricted to one food plant, and if a suitable plant does not occur on an island they will be unable to colonize it even if they are able to reach it

repeatedly. The beautiful butterfly *Danäida archippus* is widely distributed in North and South America. It is a powerful flyer and large flocks often make extensive migrations, and it is now found in many Pacific islands including the somewhat bare atolls of the Ellice group. It reached New Zealand in 1840, Hawaii in 1845–50, the Marquesas about 1860, and Tonga and Samoa between 1860 and 1870. Its food plant is a weed introduced by shipping; but it is thought that the butterflies arrived by flight. If this is so, since it feeds only on a plant of recent introduction, this butterfly must have been flying about the Pacific ocean for countless ages without being able to colonize the islands it reached, for lack of food.

An instance of the way in which human interference can disturb the balance of nature is given by events reported on Wake island a few years ago. After the establishment of the Pan-American Airways station on one of the islets there, the large numbers of rats were found to be a great pest. Finally, resort was had to poison and the rats, ravaged by thirst, died in large numbers at the water's edge. The islets teem with hermit crabs, the common sea-shore scavengers of atolls. They devoured the rats, but in turn died, in thousands. The sea birds, which had not eaten the rats, devoured the hermit crabs, and within three weeks of the initial operations they also lay dead on the beach in large numbers, sufficient to create a most unpleasant stench. Since the scavenging hermit crabs had been practically wiped out there was now no natural means of disposal of the decaying corpses of the sea birds. The upshot was that rat-poisoning was cancelled, and as soon as it was thought that the effects of the poison had passed, quantities of hermit crabs were secured from another islet and released in the hope that the faunal balance would once more be restored.

Distribution of Pacific Land Fauna (Birds)

An analysis of the distribution of the families of land birds in the Pacific islands will serve to illustrate the pattern of the distribution of the land fauna in general, and it will be seen how well the distribution of the land birds agrees with that of the insects as indicated by Zimmermann's map (Figs. 69 and 70.) The Hawaiian islands are so isolated and have consequently such a special fauna that it will be well to deal with them separately; the Galápagos and Juan Fernández also come in quite a separate category. Almost the entire land fauna of the rest of the Pacific area has migrated from the west and is either Australian, Papuan or Asiatic in origin. Nearly

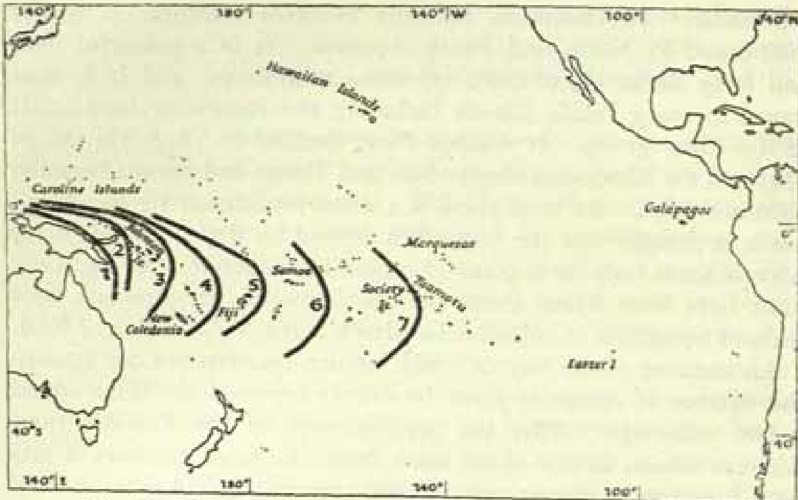


Fig. 69. Eastern limits of ranges of New Guinea land birds

1, Pelicans, storks, ibises, orioles, nuthatches, birds of paradise; 2, cassowaries, bee-eaters, nightjars; 3, true owls, water kingfishers, pygmy parrots, cockatoos, pipits, sunbirds, hornbills; 4, crows; 5, hawks, babbling thrushes, brush turkeys, thick-knees; 6, honey-eaters, thrushes, weaver-birds, white-eyes, cuckoo-shrikes; 7, barn owls, starlings, shrikes; 8 (no eastern limit), plovers, sandpipers, snipes, rails, cuckoos, wood kingfishers, lories, turtle doves, herons, pigeons, fruit pigeons, swifts, flycatchers. Based on various sources.

all the birds belong to families with representatives in New Guinea and it will be convenient to start with the New Guinea families.

(1) The pelican, stork, ibis, oriole, nuthatch, and bird-of-paradise families are not found in other parts of the Pacific area, though all but the birds of paradise have a wide geographic distribution elsewhere. The birds of paradise are confined to New Guinea and North Australia and a few nearby islands. (2) Cassowaries, bee-eaters and nightjars have representatives also in the Bismarck archipelago. (3) True owls, water kingfishers, king crows, pygmy parrots, cockatoos, pipits, sunbirds, and hornbills are found in New Guinea, the Bismarck archipelago and the Solomons, but not further east in the islands under consideration. Crowned pigeons and pittas also reach the Solomons. (4) The crow family is represented also in New Caledonia. (5) Hawks, babbling thrushes, brush turkeys and thick-knees extend eastwards as far as Fiji. (6) The honey-eater, thrush, weaver-bird, white-eye and cuckoo-shrike families reach as far as Samoa. (7) Barn owls, starlings and

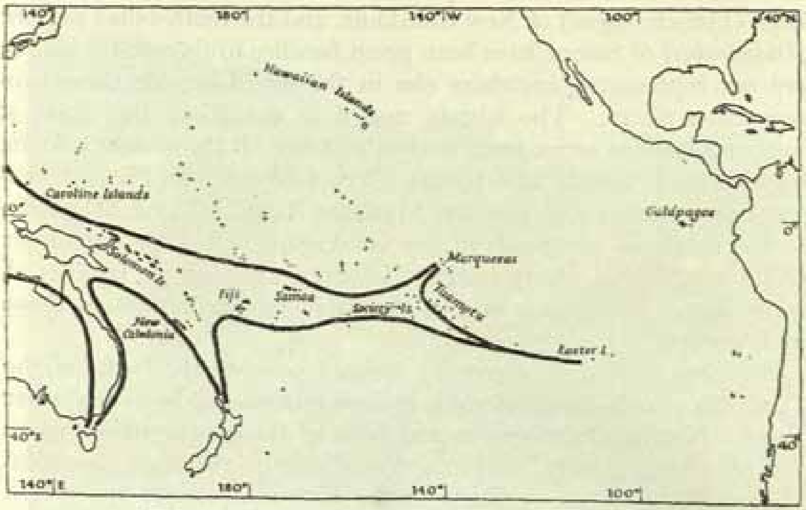


Fig. 70. Insect distribution in the south Pacific

This diagram illustrates the average normal derivations of the endemic insects of the south Pacific. Based on E. C. Zimmerman, 'Distribution and Origin of some Eastern Oceanic Insects', *American Naturalist*, vol. LXXVI, pp. 280-307 (Boston, 1942).

shrikes extend to islands to the east of Samoa, but do not reach as far as the Marquesas. (8) Finally, of the New Guinea birds, plovers, sandpipers, snipes, rails, cuckoos, wood kingfishers, lories, turtle doves, herons, pigeons, fruit pigeons, swifts and flycatchers extend over the whole of Melanesia and Polynesia, including the Marquesas.

The families so far considered all have a fairly continuous distribution and the general picture is clear that as one passes eastwards some form of animal life is left behind every time the sea between two groups of islands is crossed. The number of families with discontinuous distributions is too small to upset this picture. The swallow family is represented in New Guinea and extends eastwards as far as Fiji; then there is a wide gap until it reappears in the Society islands. The warblers are found in New Guinea, the Bismarck archipelago and the Solomons, and there are a number of endemic species in the Austral islands, the Society islands and in the Marquesas; but they are absent from the whole of intervening western Polynesia. Bustard quails, grebes and frog-mouths are found in New Caledonia; but not in the New Hebrides or the Solomons. Honey-peckers occur in New Guinea and the Bismarck archipelago and also in the Tuamoto archipelago. The flightless

kagu (French, *kagou*) of New Caledonia, and the tooth-billed pigeon (*Didunculus*) of Samoa have been given families to themselves which are not represented anywhere else in the world outside these two respective places. The islands named in the above lists form a fairly continuous series from west to east and all the groups contain high volcanic islands with forests. The Gilberts, the Phoenix and the Ellice islands and also the Marianas, Carolines and Marshalls to the north are all groups of low coral atolls with little vegetation and a much more scanty fauna. However, many of the families of birds found to the east of Fiji also have representatives in these atoll groups.

As a result of their extremely isolated position the fauna of the Hawaiian islands does not show a close relationship with any other fauna. Nearly all the species and most of the genera are endemic. There is one fimily of birds, the brightly coloured, beautiful Drepanididae, which is found in the Hawaiian forests and which occurs nowhere else in the world. Of the other Hawaiian families of land birds the honey-eaters and flycatchers have representatives in the west but are unknown in the Americas. The finches are found all over the world except in the East Indies east of Borneo, New Guinea, Australia or Polynesia. The plovers, sandpipers, snipes, rails, crows, herons, hawks and owls are found both east and west of the Pacific.

The birds of the Galápagos, while largely endemic, are clearly of ultimate Central and South American origin, and include finches, humming-birds, honey-creepers, flamingoes and mocking birds. The fauna of Juan Fernández shows similar relationships to South America.

The analysis which has been given of the distribution of the birds by families brings out the general trends very well ; but it obscures one important feature, that is, the very limited range of most of the species concerned. A few species are very widespread ; but most species are restricted to a small group of islands, often to a single island. Nearly every island in the Pacific possesses some species of animal which is restricted to it and cannot be found anywhere else. Such species are very easily exterminated. Cutting down a forest on an island, for example, may mean the loss of dozens or hundreds of species of plants, birds, insects, snails and other animals which occurred there.

The sea birds of the Pacific are not of particular interest from the geographical point of view. Terns, petrels, ducks, frigate birds,

Plate 59. Great frigate birds nesting, Hatutu, Marquesas

Plate 60. Young frigate bird
The brown adult plumage is beginning to grow through the white down.

Plate 61. Black-footed albatross and young, Laysan, Hawaiian islands

Plate 62. Love tern, Wake island

These birds are snow-white, with jet black bill and eyes. The under surfaces of the wings reflect blue and green colours from the water.

boobies and tropic birds are widespread. Frigate birds (Plate 59) are the most completely aerial of sea birds; they never alight on the water or on level land but fly in the air all day and rest in trees or on a slope at night. Their food consists of fish and other creatures picked up from the surface of the water in flight. They also chase other sea birds and force them to disgorge their food for them. Cormorants are strangely absent from tropical Polynesia but are found in some parts of Melanesia, and there is a flightless species in the Galápagos. The cold Peru (Humboldt) current flows northwards off the South American coast, and although they are right on the equator the Galápagos have a species of penguin (*Spheniscus mendiculus*). Elsewhere in the Pacific, and in the southern oceans generally, penguins (except for the Humboldt penguin, which breeds at 6° S on the coast of Peru, and the blue penguin, which breeds as far north as Moreton bay in Queensland) are limited to higher latitudes. They are found on the shores of Antarctica and in the islands of the south-west Pacific, including the Kermadecs. There are three species of albatross (Plate 61) in the area, two of which breed in the Hawaiian and other Pacific islands, and the third in the Galápagos.

Life in the Ocean

All the life in the sea, as on land, is ultimately dependent on the sun for its energy. Plants use this energy to build up the organic substances required in their structure from carbon dioxide and certain essential minerals dissolved in the water. Animals build up their bodies by feeding on plants or other animals, or on the remains of plants or animals. The depth to which light penetrates depends on the turbidity of the water, but even in clear open waters there is insufficient light to support much plant life below about 100 fathoms. The only plants found below this level must be dead, and all the animals are either scavengers or carnivores. Thus the amount of light in the different depths of the sea primarily determines the development of plant life and thus influences the animal life secondarily. It has also an influence on the coloration of animals and on their vision.

Traces of light can be detected by photographic means to a depth of over 500 fathoms in the open subtropical ocean. The more nearly the poles are approached, the shallower is the depth at which plants get enough light for growth, so the plants and the animals dependent on them for food are concentrated near the surface.

The temperature relations of the water are of great importance to the understanding of marine zoogeography. The temperature of the sea varies with location and also with the seasons. The polar and tropical seas have relatively uniform temperatures throughout the year. The annual range of surface temperature is less than 7° F. on almost three-quarters of the ocean surface, and on one-third of this, especially in the tropics, it is less than 3° F. The greatest variations appear in localities where warm and cold currents meet and predominate by turns. As the temperature of the surface of the water is raised by the sun's heat in the summer months the water decreases in density; as a result it stays at the surface, and there is a gradual decrease in temperature with depth. Over 80% of the ocean floor is more than a mile below the surface and has a temperature of 37° F. or a little less. The radiant heat of the sun does not reach deep into the water and the effective distribution of the heat in the depths is accomplished by water movements. The colder, and hence denser, waters of the polar seas sink and flow slowly along the ocean floor towards the equator and are replaced by warmer water in surface currents. On lee coasts within the influence of the trade winds, the warm surface water is continually blown away and driven against the windward coasts. This is compensated for by an upward flow of cold water. The lower waters are often separated from the surface layers by a very definite boundary, or discontinuity layer; there may be several strata of water of different origins and different densities one above the other. There is usually a sudden drop in temperature as the discontinuity layer, or thermocline, is crossed from an upper to a lower layer. These discontinuity layers impede the mixing of the waters and there is a marked difference in the physical properties and the chemical and biological content of two adjacent strata. A discontinuity level is found in all warm seas and usually lies between 25 and 75 fathoms.

The chemical content of sea water is remarkably constant as a slow but complete mixing of all layers takes place. The slight differences in composition which do occur are, however, of great importance biologically. Phosphates and nitrates are minerals essential for plant life, and they are present in sea water in such very small amounts that the growth of plant life and thus also of animal life of a given part of the sea is limited by their concentration. Plants can only make use of them where there is light, and so the phosphates and nitrates are rapidly used up in surface waters but accumulate lower down. The plants have to secure them from an

extremely dilute solution and this necessitates that they be of small size in order to have a high ratio between area of surface and bulk. In contrast to the plants on land, the marine plants which form the basis of the food chain, even for fishes and whales, consist of microscopic diatoms and other even smaller plants. The loss of these minerals from the surface waters is increased as the bodies of many dead organisms which have fed on the plants sink below the plant-inhabited layers. Here the nitrogen and phosphate content of the water cannot be used and so the concentration increases with depth. The fertilization of the lighted upper waters by nitrogenous compounds occurs largely through the upwelling of deep water and the inflow of fresh water from the land.

In shallow coastal seas the tides and storms are able to keep the waters mixed, and in temperate and cold latitudes there is a periodical mixing of the waters in consequence of the cooling of the surface water in the winter. By this means nitrogenous water is brought up from about 70 fathoms in temperate waters and from 400 or more fathoms in Arctic and Antarctic waters. A great outburst of diatom growth follows in the spring when the light increases. On coasts where continued off-shore winds carry away the surface waters a compensating current rises from the depths, carrying with it nitrates and phosphates. No oceanic waters swarm so with life as the upward streams of deep water when they reach the surface in tropical latitudes. The coast of Chile with its cold upward currents is especially notable for the wealth of its marine life, and the nitrates of the guano deposits have come from this source through a complex series of food chains of the type: diatom, copepod, fish, bird. Vertical mixing also occurs where a warm current passes a cold one, and again a rich fauna results.

In tropical oceans generally, however, there is comparatively little life as there is very little mixing of the waters. The scarcity of life in tropical waters may however be partly illusory. The temperature is high and the biological processes are greatly speeded up so that a life history may only take a few days instead of several weeks. Another contributory cause of the poverty of life in the open south-eastern Pacific is the fact that compared with other oceans the Pacific has very few long rivers flowing into it. Nearly three-quarters of the extent of the entire Pacific ocean is 2,000 fathoms or more deep, and there are no continental shelves on the west coasts of the Americas.

Oxygen is present in sufficient quantities for life at all depths in

the open oceans. It is naturally most abundant near the surface, especially in the lighted zone where it is given off by the planktonic plants. Towards the bottom of this zone plants absorb as much as they give off and at a depth of about 250 fathoms there begins to be some deficiency. At greater depths, however, there is less food supply and so there are fewer animals to use up the oxygen. As it is being constantly brought in from high latitudes the great ocean depths have an oxygen content only a little below normal. If it were not for this circulation the oxygen would soon be all used up. In some parts of enclosed seas like the Mediterranean and Baltic there is no such bottom current and carbon dioxide accumulates and there is lack of oxygen. In deep inland seas and in some isolated bays and harbours where there is a rich surface fauna and stagnation in the bottom waters, the lack of oxygen becomes so great at the bottom that the hydrogen sulphide produced by the decomposition of animal matter is not oxidized and accumulates. In extreme cases, such as at the bottom of the Black sea, all life becomes impossible.

Pelagic Animals

Pelagic animals may be grouped according to their ability to swim freely (that is, independently of the oceanic currents) or according to their dependence on the latter. Those whose independent movements are insignificant in comparison with the movements of the water belong to the plankton. All animals less than half an inch long which are suspended in the water, either at the surface or in deeper layers, come under this category and so do many of the larger forms, particularly the jellyfish. Nearly every group of invertebrate animals has representatives in the plankton. A great many bottom-living and sedentary animals are planktonic during the early stages of their life history; worms, starfish, oysters, crabs (including land crabs), corals and many fishes have free-swimming larvae which drift in the surface waters. While the total number of individuals in a given volume of water is comparatively small in the tropics, there is a much greater variety and there are many more species than in higher latitudes.

Living matter is a little heavier than water and so planktonic animals have special adaptations to prevent them from sinking. As far as possible the specific gravity is reduced, and shells are very thin or absent. Jellyfish, pteropods, pelagic bristle-worms, squids, and some feebly swimming fish all take up large quantities of water so that their tissues are light, transparent, and jellylike (Fig. 71).

Flotation is aided in many of the animals, from protozoa to basking sharks, by accumulations of fats and oils. Gas is present in the floats of the Portuguese Man-o'-War and the By-the-Wind-Sailor, and also in the air sac of bony fishes and the lungs of sea snakes,

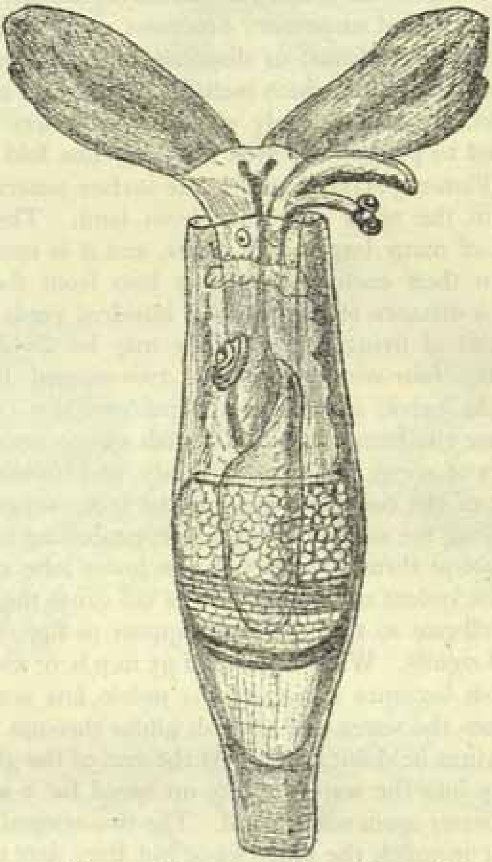


Fig. 71. A pteropod (or sea butterfly)

An example of a mollusc showing a number of modifications of structure for pelagic life. The body is perfectly transparent and gelatinous ; the shell is very light and paper-like ; and the 'foot' is modified into a pair of flapping 'wings'. About three-quarter natural size. Drawn by J. P. Harding.

turtles, seals and whales. A large number of small planktonic organisms of different kinds retard the rate at which they sink through the water by having long spines or feathery processes, or by extreme flattening so that the frictional resistance to sinking is

greatly increased. Several examples are shown in Fig. 72. Many pelagic animals keep up in the water by active swimming. Feeble swimmers like jellyfish and pteropods direct most of the energy of swimming to opposing gravitational pull, and there is very little movement in a horizontal direction. Better swimmers adopt more streamlined shapes, and suspensory processes are placed in the plane of motion (as in *Calocalanus*) or dispensed with altogether. The fish of the mackerel group, which includes the bonitos and albacores of tropical seas, are all extremely vigorous swimmers and streamlining is carried to perfection; even the body fins fold into groves.

Flying fish (Plates 63–4) are found in the surface waters of all warm seas, mostly in the open ocean far from land. They form the principal food of many large ocean fishes, and it is mainly in order to escape from their enemies that they leap from the water and then glide for a distance of two or three hundred yards. There are about 50 species of flying fish and they may be divided into two main types, the four-winged and the two-winged forms. The former have the pelvic as well as the pectoral fins enlarged into 'wings' and are the better fliers. The fish swims rapidly upwards with both pairs of wings folded to the body, and breaks the surface with the front of the body and spreads the front wings. The fish then 'taxis' along the surface of the water, propelling itself forward by powerful lateral thrusts of its tail, the lower lobe remaining in the water. The violent movements of the tail cause the whole body and wings to vibrate so that the latter appear to flap, though they are in fact held rigidly. When a speed of 35 m.p.h. or more has been attained the fish becomes airborne; the pelvic fins are raised, the tail is lifted from the water and the fish glides through the air with both pairs of wings held out stiffly. At the end of the glide it either dives gracefully into the water or gets up speed for a second flight by lashing the water again with its tail. The two-winged forms glide through the air in much the same way; but they dart directly into the air from the sea and return with a splash at the end.

Most planktonic organisms make vertical diurnal migrations and move upwards at night. The surface water of the oceans become much richer in plankton at night for this reason.

The minute plants and the small animals which feed on them directly, including particularly the copepod crustacea, which comprise 90% of the fauna, occur in enormous numbers. A great many of the pelagic animals of all kinds and sizes, ranging from small crustacea less than a quarter of an inch long to the largest

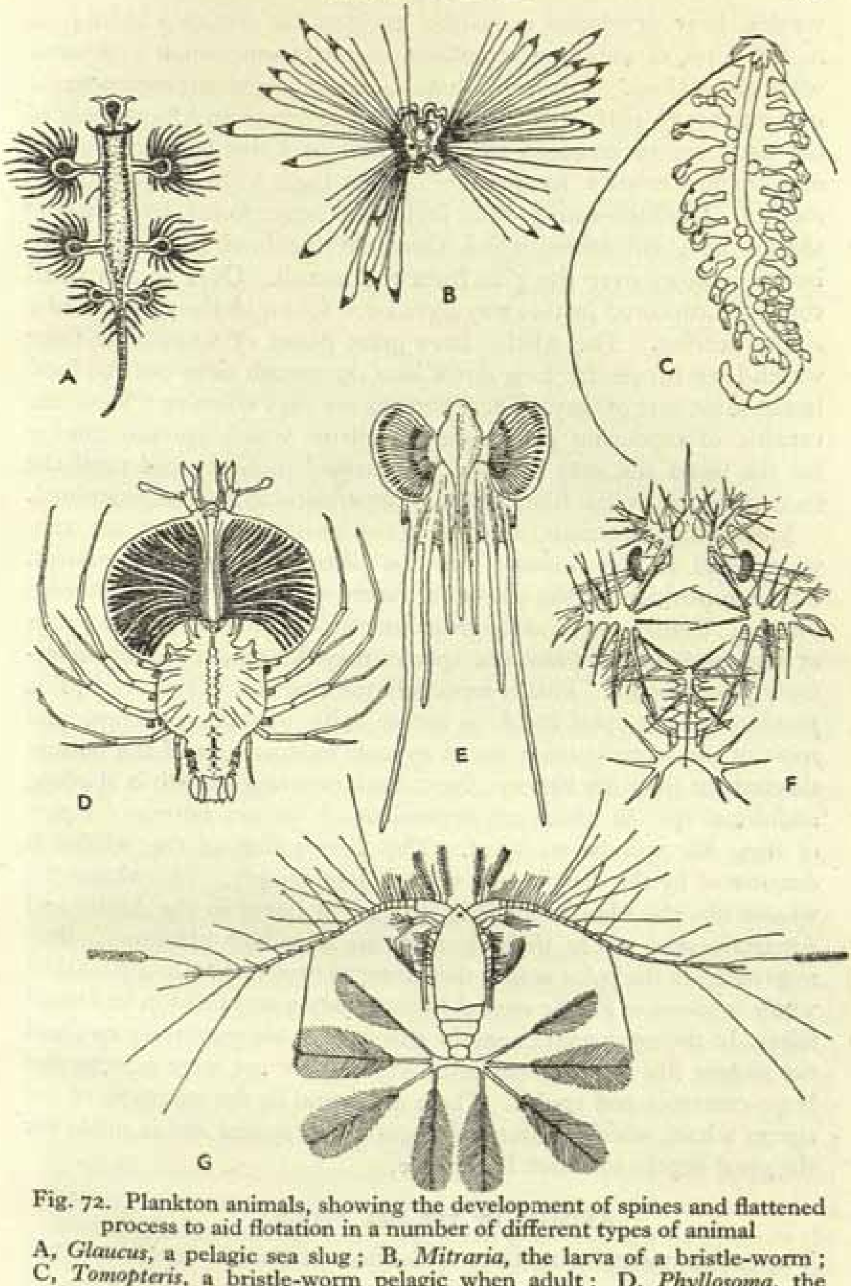


Fig. 72. Plankton animals, showing the development of spines and flattened process to aid flotation in a number of different types of animal

A, *Glaucus*, a pelagic sea slug ; B, *Mitraria*, the larva of a bristle-worm ; C, *Tomopteris*, a bristle-worm pelagic when adult ; D, *Phyllosoma*, the larval form of the crustacean *Palinurus* ; E, *Lophius*, the pelagic larva of a bottom-living angler fish ; F, *Sergestes*, a crustacean larva ; G, *Calocalanus*, a copepod. Based on W. C. Allee and K. P. Schmidt, *Ecological Animal Geography* (New York, 1937).

whales, have developed sieve-like strainers for securing their food in the form of enormous numbers of organisms, small compared with themselves. Copepods have a complicated arrangement of moving mouth-parts with bristles. The structure and movement of the parts are so arranged that a current of water flows through a mesh of fine bristles, leaving the food on them to be raked into the mouth. Plankton-eating fish, including large forms like basking sharks, have gill rakers which sieve out the food from the water before it flows over the gills from the mouth. Over 60,000 small copepods captured in this way have been found in the stomach of a single herring. The whales have great plates of whalebone from which long fringes hanging down into the mouth sieve out the food in the same sort of way. These screens are very effective; some are capable of capturing planktonic organisms which are too minute for the finest silk nets and which remained undiscovered until the food collected by the filter plates of appendicularians was examined.

Most pelagic animals, whether active swimmers or not, are very widespread in the oceans; but the distribution is not uniform. The composition of the plankton varies with time as well as with locality. Usually there are a great number of different species; but at a given time and place one species may flourish and overwhelmingly predominate. This is especially the case in shallow seas. The plankton of the open Pacific is not so liable to sudden changes and most of the fauna is made up of animals independent of the bottom throughout their life history. Near land, or where the sea is shallow, additional species which are dependent on the sea bottom for part of their life will be included. The distribution of the whales is dominated by the distribution of their food supply. The whalebone whales like the blue whale (Fig. 73) are at home in the Arctic and Antarctic seas where there is such an abundant plankton; they migrate from the polar seas in the winter to breed. The hump-backed whale is found in Pacific coastal waters feeding on plankton and small fishes. In the open warm seas the plankton is comparatively rare and the richest life is at a lower level where there are large numbers of large crustacea and squids. These are found in the stomachs of the sperm whale, which is found in these warm waters and is noted for the great depths to which it can dive.

Animals of the Sea Floor

The environmental conditions of the floor of shallow waters are very varied and the fauna is very rich; perhaps the most important of

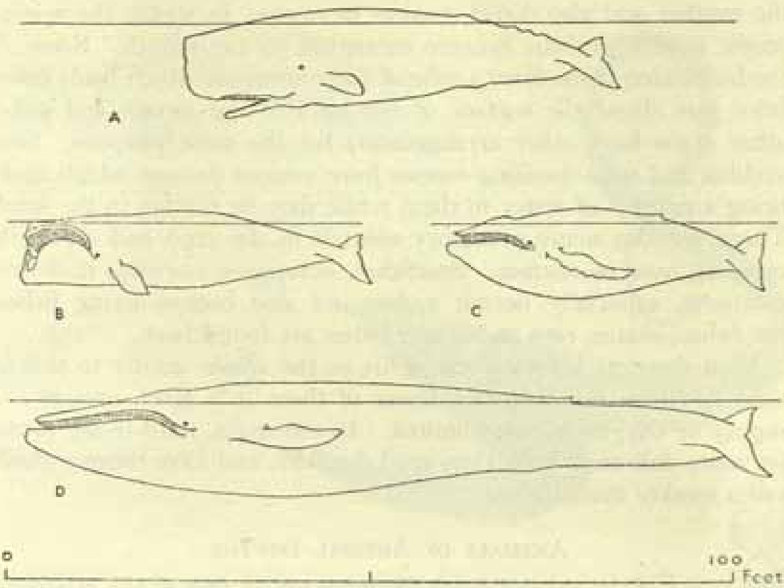


Fig. 73. Whales found in the Pacific ocean

A, sperm; B, black right; C, humpback; D, blue. Based on various sources.

the many factors concerned in determining the nature of the animal community is the type of substratum. The crannies found along rocks provide shelter for a great many different kinds of animals and the rocks provide a substratum for sedentary forms; in the Pacific, coral reefs provide this type of environment in shallow waters and these will be described later.

Burrowing animals of all sorts are characteristic of sandy bottoms. Many, particularly the worm-like forms, ingest the sand and digest the organic debris it contains as it passes through the body. These forms need specially well developed gills with an extensive surface well supplied with blood to take in the scanty supply of oxygen in their surroundings. Other forms remain more or less stationary in their burrows and have some arrangement which causes a current of water to flow through a sieve and over the gills bringing both food in suspension and oxygen in solution. The numerous species of sand-living bivalve molluscs have a pair of hollow siphons protruding above the surface of the sand, one leading to and one away from the gill chamber. The gills are in the form of very fine nets with the meshes covered with microscopic cilia which lash the water through

the meshes and also direct streams of mucus, in which the microscopic food organisms became entangled, to the mouth. Some of the burrowing crabs form a tube of their antennae which leads down from just above the surface of the sand to the mouth and gills; other crabs have other arrangements for the same purpose. Sea-urchins and tube-dwelling worms have various devices which again bring a current of water to them while they lie hidden in the sand. There are also many predatory animals in the sand and especially creeping over its surface. Starfishes, octopuses, univalve molluscs, crustacea, especially hermit crabs, and also bottom-living fishes, flat fishes, skates, rays and angler fishes are found here.

Mud dwellers have a mode of life on the whole similar to that of sand dwellers, but there are fewer of them in a given area as the supply of oxygen is more limited. In the main, mud-living forms are more delicately built than sand dwellers, and have thinner shells and a weaker musculature.

Animals of Abyssal Depths

The fauna of the abyssal depths is quite unlike that of the relatively shallow waters which lie outside the geologist's Pacific basin (p. 14). The conditions are so different, and there can be very little interchange between the populations of the two zones across the slope which connects them. Conditions are more unchanging in the abyss than anywhere on the earth's surface. There is no difference between day and night or summer and winter. The waters are absolutely still and silent and uniformly cold and dark. The pressure is very great, from two to five tons per square inch; but as the pressure inside the animals is as high as it is outside they come to no harm. As a result of the complete absence of water movement, other than the very slow circulation described above, most of the animals are very gracefully and delicately built; even the pelagic fish have delicate, fragile skeletons and feeble muscles at these depths.

Most of the bottom is uniformly covered with a deep layer of soft ooze of the consistency of summer butter, and animals living on it require some means of support. Some of the sedentary animals, sea lilies and the like, have root-like growths and long stalks. The sea urchins which creep over the ooze are often flattened so as to spread their weight over a wide surface, and many of the crustacea have very long slender limbs with the terminal joints expanded by a fan of bristles to increase the supporting surface.

No plant material is available for food so the animals are all either

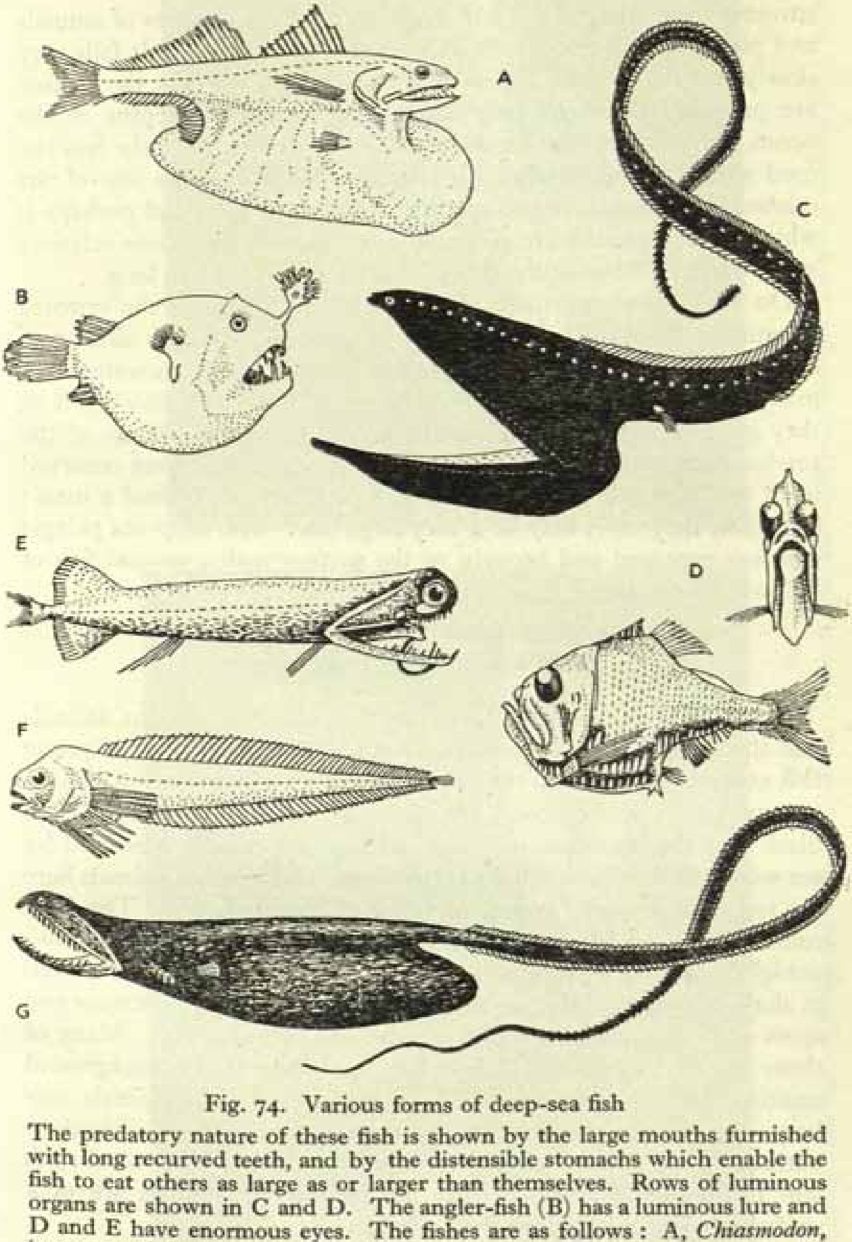


Fig. 74. Various forms of deep-sea fish

The predatory nature of these fish is shown by the large mouths furnished with long recurved teeth, and by the distensible stomachs which enable the fish to eat others as large as or larger than themselves. Rows of luminous organs are shown in C and D. The angler-fish (B) has a luminous lure and D and E have enormous eyes. The fishes are as follows: A, *Chiasmodon*, 'great swallower'; B, *Borophiyne*; C, *Eurypharynx*, 'gulper'; D, *Aegyrepelecus*, 'hatchet-fish'; E, *Malacosteus*, 'wide mouth'; F, *Paraliparis*; G, *Saccopharynx*, 'gulper'. Based on J. R. Norman, *A History of Fishes*, p. 231 (London, 1931).

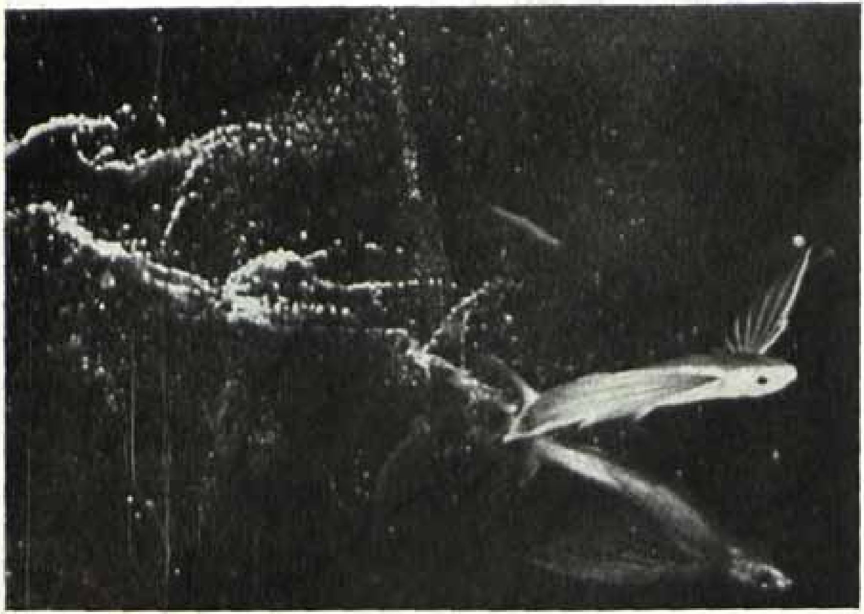
scavengers or predators. Food in the form of the remains of animals and plants from higher levels falls gently to the depths. It falls very slowly and most of the bodies of animals which die near the surface are probably devoured long before they reach the depths of the ocean. So, under equal conditions, the deeper the ocean the less the food supply which reaches the bottom. This must be one of the reasons why animals are so sparsely distributed here, and perhaps is why deep-sea animals are generally much smaller than their relatives at the surface. Most of the fishes are only an inch or two long.

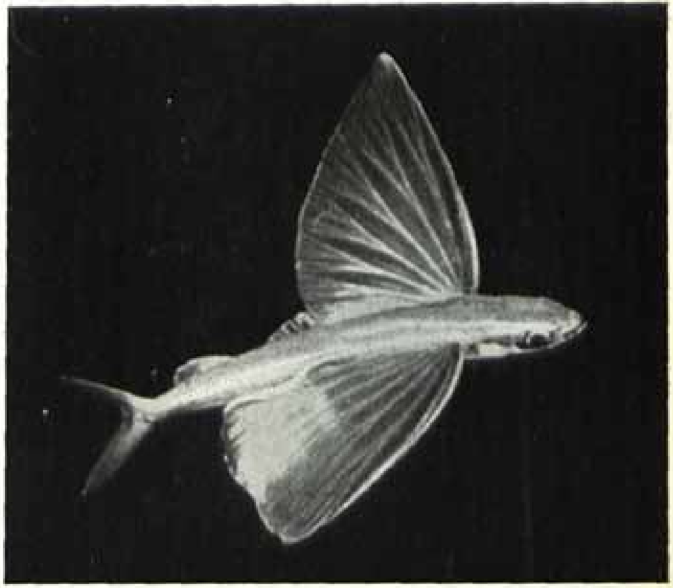
On the bottom are many detritus feeders living on the remains of animals from all levels above. In general these are similar to detritus and mud feeders of shallow waters. Sea cucumbers of many colours plough their way through the ooze, swallowing it as they go and extracting what nourishment they can. Many of the predatory fish have very wide mouths furnished with long recurved teeth and distensible stomachs (Fig. 74). They rarely find a meal; but when they do it may be a very large one. One deep-sea pelagic fish was captured and brought to the surface with a second fish of its own species larger than itself in its stomach.

Colour and Phosphorescence

There is a close correlation between the colours of marine animals and the depth at which they are found. The majority of the young fish and other animals in the upper waters are colourless and glassily transparent. Below about 300 fathoms the fishes are nearly all black and the crustacea red. As red rays are rapidly absorbed by sea water, there is no red light at this depth and to other animals here the red crustacea will appear as black as the black fish. The dark coloured fish are found nearer the surface in high latitudes and also at night. Animals living among rocks and weeds or on sand or gravel, in shallow lighted water, are often brightly coloured with stripes and spots and other patterns which match their surroundings. Many of them are able to change their colour according to the background against which they are seen. Poisonous or distasteful animals may have conspicuous colouring to warn predators of their obnoxious nature. The brilliant colours of animals associated with coral reefs will be discussed later. Nearly all deep water animals are of a uniform colour, black, red, grey or white.

Many marine animals are luminous. The phosphorescence of the sea on a dark still night is the result of the activities of a great





Plates 63, 64. Flying fish

These high-speed photographs show (left) the fish taking off, leaving a wake of spray and bubbles, and (right) the fish in mid-air with 'wings' outspread.

Plates 65, 66. Sections of coral reef.

Plate 65 (left) shows the coral left exposed by the receding tide; branching *Montipora* can be seen in the foreground, with a fully contracted soft coral behind. Plate 66 (right) is a view looking down into a moat where the coral remains covered with a constant level of water at low tide. Branching *Montipora* and massive colonies of *Favia* can be seen in the coral sand between. A large boulder of dead coral in the left-hand bottom corner is being recolonized by a *Favia* in the centre.

many different kinds of animals. *Noctiluca*, a protozoon, is the one most often named; but many of the small planktonic animals contribute. The lower forms may give off a luminous secretion from the general body surface. Some of the copepods have special glands which discharge a luminous substance into the water so that little clouds of phosphorescence are formed. Many of the small jellyfish carry a girdle of little lights which flash in unison. Light-producing organs are developed to their fullest extent in larger animals living in deeper water. Complex organs arranged in rows along the sides and on the head have been evolved independently in such different groups of animals as decapod crustacea, squids and fishes. They are like little searchlights and are complete with reflector behind and lens in front, and sometimes a coloured filter is incorporated so that the light, instead of being white, is blue, green or red. These organs are under direct nervous control and can be switched on and off at will. Light organs are rarely developed in animals confined to coastal or boreal waters; they are most fully developed in animals from depths near to the limit of light penetration, and gradually decrease in size at greater depths. In very deep water and on the bottom these special light-producing organs are rare, though many of the bottom-living worms and other invertebrates secrete a general luminescence. The eyes of pelagic fish and crustacea also tend to become small and imperfect in depths below 250 fathoms and below a certain depth most forms are blind. Most bottom-living fishes, on the other hand, have very large eyes, even in the greatest depths of the ocean. Presumably there is sufficient general luminescence produced by bottom-living invertebrates for those eyes to be of use. Probably the pelagic deep-sea fish are blind because the population is too sparsely distributed for there to be enough light from what luminous organs they may possess.

Octopuses are bottom-living animals and do not develop light organs like their pelagic relatives the squids; but their eyes are often large. The light is produced by all these different animals by the secretion of luciferin and its subsequent oxidation in the presence of luciferaze. It is an extraordinarily efficient process as the light is cold and none of the energy is lost as heat.

The function of luminous organs is very little understood; in some cases where the animal remains buried in mud and the light can never show, the luminescence is probably only a by-product of metabolism and may serve no useful purpose. Animals living in burrows, like the rock-boring piddock and some of the tube-worms,

are also hidden from view; but it is possible that the light tends to attract into the burrows minute animals on which they feed. In gregarious swimming animals luminous organs may help individuals of the same species to recognise each other, and one member may be able to see its prey against the background of light produced by its fellows. No doubt they often serve to attract the sexes in the breeding season. The natives of some islands use the luminous organs of fish as bait with a success which suggests that their rightful owners may also find them useful for attracting their prey. Some of the deep-sea angler fishes do in fact dangle a luminous lure, on the end of a long tentacle, in front of their gin-like mouths. The sudden flashing of light may dazzle or distract a pursuing enemy, or the lights may serve as a warning that their owner is harmful or unpalatable as food.

Types of Corals (Plates 65-75)

Corals belong to the group of animals known as Coelenterata which include sedentary forms like sea-anemones, hydroids and corals and free-swimming forms like jellyfish. The basic structure of all is the same and consists of a hollow double-walled body open at one end and fringed round the opening by tentacles. The tentacles are armed with tiny capsules which explode on contact with any floating or swimming organisms and some of the capsules shoot poisoned darts into the organisms while others shoot out adhesive threads. The prey is paralysed and adheres to the tentacles which are then curved round to push the prey through the mouth into the stomach, where digestion takes place by the secretion of enzymes by the inner wall, any indigestible remains being ejected by the mouth. In many forms the structure is considerably more complicated than the basic pattern described above. A great many coelenterates, both sessile and free-swimming forms, have a vegetative type of reproduction known as budding; young individuals grow out of the side of the parent in much the same way as a branch grows out of a tree. By successive budding a colony of many individuals is formed. The stomach cavities of all the individuals of a colony generally remain continuous with one another so that what is eaten by one individual helps to nourish the whole colony. In many coelenterates certain individuals of the colony specialize in feeding and others have no mouth but specialize in other functions, such as sexual reproduction.

If the simple hollow pattern were adhered to by the larger forms,

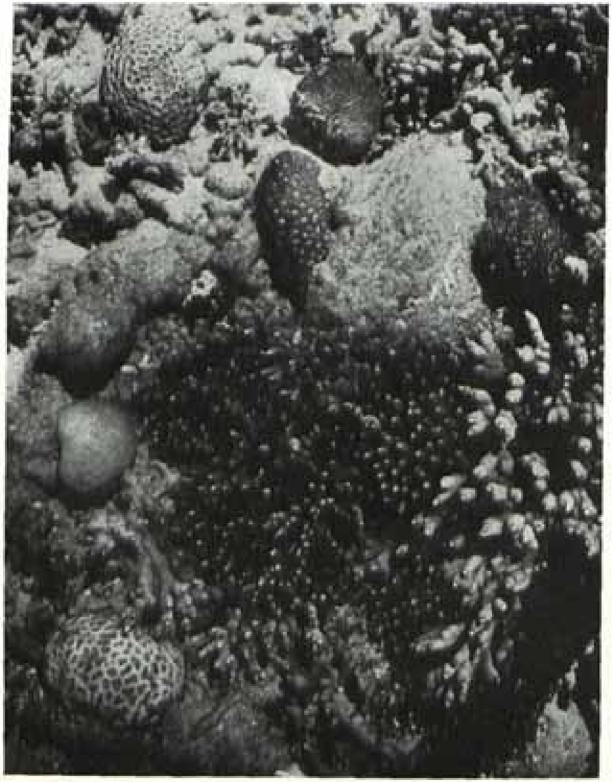


Plate 67. View downward, vertically, through the water over a reef

In addition to the branching *Montipora* and three colonies of *Favia*, there is the solitary coral (*Fungia*), top centre; a brain coral (*Meandrina*), right centre; and a small colony of *Porites*, on the left.

Plate 68. *Flabellum*, a solitary coral

In the upper example, the tentacles are expanded, so that the mouth is hidden; in the lower, they have contracted into a groove, and the lower limit of the soft tissue lips over the cup-like skeleton below.

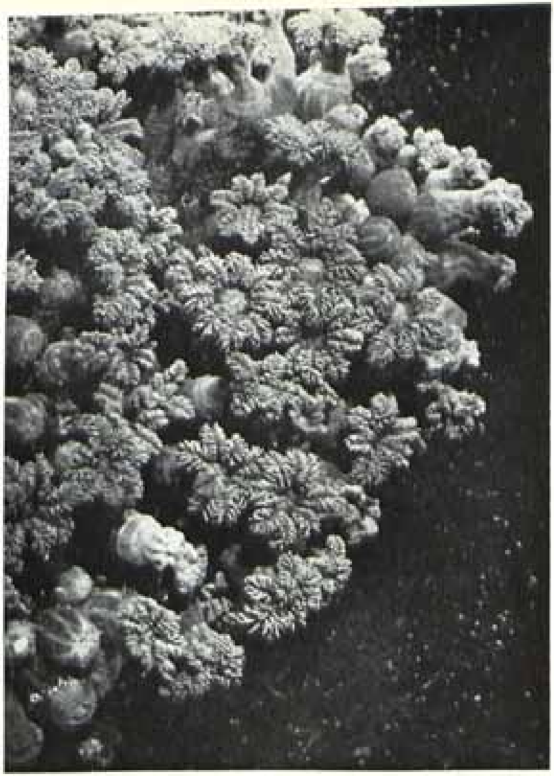


Plate 69. A colony of the Alcyonarian coral *Clavularia*
The individual polyps can be seen in all stages of expansion and contraction.

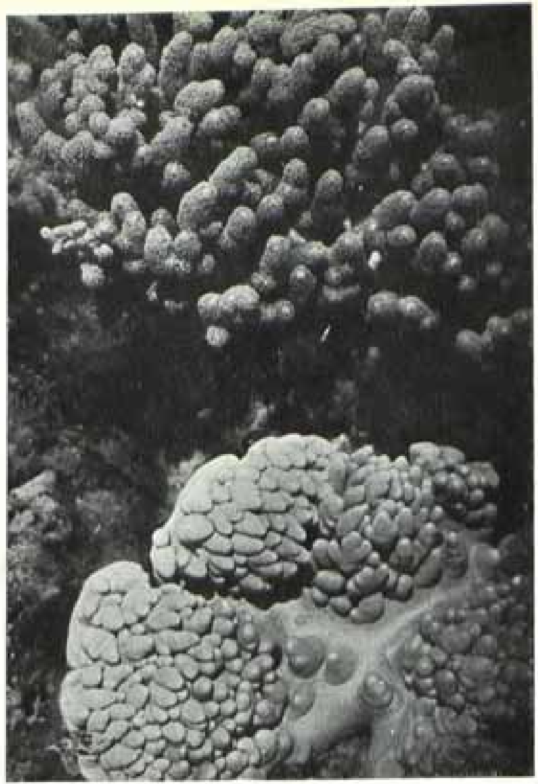


Plate 70. *Simularia*, a soft coral
The upper colony and its polyps are fully expanded. The lower has been heavily stamped upon with rubber boots and is fully contracted.

the anemones and many corals would have too small a digestive area for their bulk, so the wall of the stomach has radially arranged partitions growing inwards and thus increasing the surface. Many coelenterates have no skeleton, but those that do often have massive skeletons of calcium carbonate; these are known as coral.

There are three main types of coral. The most important corals are the madreporarian or 'stony' corals; these are mostly colonial and are of the sea-anemone type and form a thick skeleton around and below each individual. Each individual polyp sits in a pit in the skeletal mass, the floor of which is raised into sharp radially arranged ridges. The presence of these ridges, or septa, is characteristic of the stony corals. The coral may be solitary as in the case of *Fungia* (Plate 67). This is a coral common in tropical waters, and is so called because the septa look very like the gills of a mushroom, and the coral is itself very much the shape of the head of a mushroom lying with gills uppermost. When young, *Fungia* is fixed to the ground on a stalk, but later it becomes detached and drops on to the sand, where it continues to grow until it is about 6 in. across; in spite of its weight it avoids being buried by removing any sediment which falls on it as rapidly as it is deposited. Few reef-building corals are free as is *Fungia*, or possess such large individual polyps.

Most of the reef-building corals form great colonies of many smaller individuals, all derived by budding from one original polyp, and the skeletons of all the individuals of a colony are united to form a great stony mass of coral. The final shape of the mass depends on two things, the species of coral by which it is built and the conditions under which it is growing. In some species all the polyps have equal powers of division and budding, and in these the colony may spread in a regular fashion over the substratum as an encrusting layer, or a more or less spherical mass may result. In others the growth is uneven, and lobed or branching colonies are formed. In the 'brain' corals separation of one polyp from the next is incomplete and does not extend to the skeleton, and as the mouths and tentacles are arranged in sinuous lines the surface of the rounded mass of coral has wandering grooves resembling the convolutions of the cerebral hemispheres of the brain. The stag's-horn corals grow in branching tree-like forms; the polyp at the apex of a branch grows most rapidly, budding off side polyps as it lengthens. When the branch has reached a certain length a side polyp some distance from the apex starts a new branch.

During the daytime most corals are inactive. The polyps expel water from their bodies and shrink down each into its pit in the skeleton, so that the latter is visible through the thin transparent living tissue, with a keyhole-shaped mouth in the middle of each pit. At night, however, a reef presents a very different appearance, as the polyps are all expanded and the body and tentacles of each elongate enormously and project far beyond the skeleton, so that the general surface of the colony may be obscured by a forest of tentacles spread out for catching food (Plates 69, 70, 75). At night the upper layers of the sea are teeming with microscopic animals and plants which sink down into deeper water by day. Corals are carnivorous and feed at night on the minute animals, paralysing them with their stinging cells and passing them to the mouth by the tentacles.

The corals so far described are of the sea-anemone type and are sometimes known as 'true' corals. All the individuals are alike, and they are the most important of the reef-building corals. Besides these there are a number of corals allied to the little hydroids, and there are also 'soft' corals (Plates 70-5). The commonest of the hydroid corals is *Millepora*, the stinging coral, which is found on coral reefs all over the world. The polyps are all united and embedded in a thick calcareous skeleton traversed by canals connecting the polyps. They are arranged in a definite pattern. The surface of the skeleton is covered with fine pores in groups, and each group has a ring of five to seven apertures with a larger one in the centre. Out of the central aperture a relatively stout and stumpy polyp emerges, this has a mouth and a stomach; and out of the smaller holes project long slender polyps without mouths but covered with little tentacles which are armed with batteries of stinging capsules, powerful enough to penetrate the human skin and cause a painful rash. The food is captured by these slender polyps and carried by them to the large central polyp where it is swallowed and digested. *Millepora* is remarkable for the great variety of the different growth forms it exhibits in different situations.

It will be remembered that the body-wall of the coral is of two layers—an inner digestive layer and an outer skin. In all the corals so far described the skeleton is secreted outside the polyp by the outer skin. In colonial forms, particularly those that are branching, this is not very obvious, as the fleshy parts of the polyps may be continuous with one another above, and cover over the skeleton secreted by their lower outer surfaces. In the Alcyonaria or 'soft' corals, however, the skeleton is formed of spicules of calcium car-

Plate 71. *Sinularia*
The colony is expanded but the polyps are contracted.

Plate 72. *Sinularia*
The colony is expanded but the polyps are contracted.

Plate 73. *Lobophytum*, a soft coral
The polyps are fully expanded on soft, flexible cockscomb-like growths.

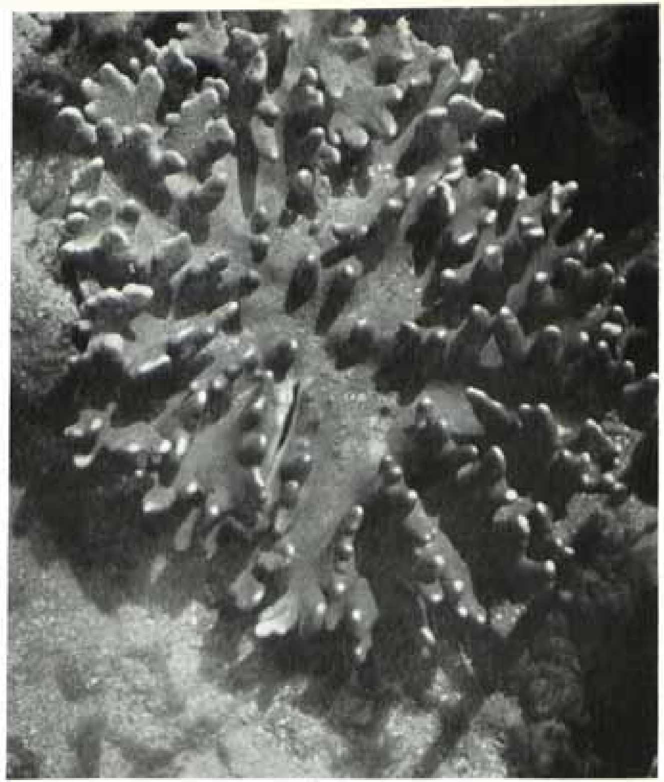


Plate 74. *Lobophytum*, contracted
The coxcombs have become reduced to smooth hard knobs, as rigid as an inflated motor-car tyre.

bonate situated inside the polyp between its outer and inner body-wall. In corals of the Dead-Man's-Fingers type the spicules remain separate and the coral grows into fleshy masses which have some powers of contraction and expansion as a whole, apart from the polyps which can sink into or extend from their pits. These colonies (Plate 66) may reach a very large size and cover several square yards. In other alcyonarians, of which the red coral of commerce is an example, the spicules are fused together to give a rigid skeleton. The red coral is not itself found on coral reefs, being confined to temperate waters, but there are others of this type which are important on reefs. The organ-pipe coral, characteristic of many exposed reef crests, has a deep red skeleton composed of a mass of parallel little tubes united together at intervals by little platforms. The living polyps with bright emerald tentacles project from the open tops of the tubes. As the colony grows older the tubes lengthen and the living coral becomes confined to the upper portions of them; the lower parts serve only to support the colony and become invaded by other animals of many kinds.

Growth of Coral Colonies

The growth form of a coral colony is very much influenced by the conditions under which it lives. This is particularly the case with branching species. Important factors in the environment concerned with the form of the coral growth are the movements of the water, the direction of the light, and the deposition of sediment. Species which grow in one plane may be so orientated that the plane of the colony is at right angles to the prevailing current, thus offering a larger surface of polyps to the food-bringing stream. In other regions, notably those of luxuriant growth in shallow water, bracket- and dish-shaped colonies presenting the maximum surface towards the light are formed. The colonies do not overlap and the bulk of the polyps are situated on the exposed sunlit surface.

The mechanical influence of the environment is considerable. It is mechanically impossible for delicate forms to exist in rough waters along the seaward edges of reefs without being broken, and if they are able to survive in these waters they must do so in compact rounded or flattened forms; and corals of the branching type growing in such places have a denser and stronger skeleton and a more compact form. Their short stumpy branches are often reduced to mere knobs. In the gently moving waters of lagoons and coral pools, species which tend to branch can do so freely, and delicately

branching forms with only lightly calcified skeletons result. In deep still water in the deeper parts of lagoons the apical polyp of *Madrepora* goes on growing undisturbed, and the polyps budded from the side remain under its dominance and do not grow into branches and have no side polyps of their own. The result is that the whole coral colony may take the form of a simple cylinder of great length and fragility, with practically no side branches.

The ability of corals to live in the gentle waters of the leeward slopes of reefs will also depend on their ability to remove sediment. Sediment rapidly kills corals if it settles on them more rapidly than it can be removed. The chief means of removal is by cilia with which the living surface is covered. The polyps of colonies living in waters where much sediment is falling tend to be relatively tall and to stand out from the general surface. Branching forms are less liable to be smothered in sediment than compact forms. When the upper surface of a coral exceeds a certain area it becomes impossible to remove all the sediment, and the polyps in the centre die. As the coral continues to grow outwards elsewhere the result is that the coral mass, at first roughly spherical in shape, becomes flattened at the top as it grows, and with further increase in size in quiet waters with much sediment, the final result may be a great shallow bowl in the hollow of which sand and other debris accumulates. Coral boulders with flat tops are also found in all regions where upward growth becomes checked by the surface of the sea and living polyps and further growth are restricted to the sides. Exceptional weather conditions, such as a thick layer of fresh water floating on the sea after torrential rains, or very bright hot weather, coinciding in either cases with a low spring tide, will cause great mortality among corals and may alter the whole facies of a reef.

The colours of a living coral reef are very striking. Not only are the corals and the calcareous algae encrusting dead coral rock of many vivid hues, but most of the other inhabitants of the shallow waters are so too. The colour of a coral is due to the living soft tissue, the limestone skeleton being usually white, and is to some extent dependent on light, for corals in deeper water generally lose their pigment. The same species of coral may be quite differently coloured even when living in what seems to be an identical environment; usually different parts of the same colony differ in colour. The brown colour of some of the corals is often due to the presence in the tissues of the body of great numbers of minute single-celled plants. Most corals, except those found in deep water, have